Gasoline Combustion Fundamentals

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Program Manager: Leo Breton & Gurpreet Singh
U.S. DOE Vehicle Technologies Office

Project ID: ACS006

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Overview

Timeline

- Project provides fundamental research supporting DOE/industry advanced engine development projects.
- Project directions and continuation are evaluated annually.

Budget

- Project funded by DOE/VTO
- FY17 funding: $700K

Barriers identified in VTO Multi-Year Program Plan

- Insufficient knowledge base for advanced LTC or mixed-mode combustion systems over the full load range
- Models are needed for fundamental engine combustion and in-cylinder emissions formation processes
- Lack of effective engine control for advanced lean-burn direct injection gasoline engine technology

Partners

- Project lead: Isaac Ekoto, Sandia National Laboratories
- Industry/Small Business Partners:
  - GM, Ford, & FCA: technical guidance
  - 15 Industry partners in DOE Working Group
  - Mahle GmbH
  - Transient Plasma Systems Inc.
- University/National Lab Collaborators:
  - Argonne National Lab: Low-temperature plasma modeling
  - U. Minnesota: Engine sample speciation
  - U. Orléans (France): In-cylinder ozone generation
  - Michigan State University: Turbulent jet ignition

Relevance & Objectives

Project Objective:

- Expand the fundamental understanding of fluid-flow, thermodynamics, and combustion processes needed to achieve clean and efficient gasoline engines

FY17 Objectives:

- Explore how low-temperature plasma (LTP) igniters can facilitate efficient, mixed-mode combustion across the load/speed map:
  - Low load/speed: In-cylinder ozone generation for controllable **LTGC**
  - Moderate load/speed: Extended dilution tolerances for **lean-burn SI**
  - High load: Improved knock resistance for **boosted SI**
- Improve foundational knowledge base of LTP ignition mechanisms through well-controlled experiments and modeling
- Benchmark LTP igniter performance in an optically accessible DISI engine
- Create hardware needed to evaluate pre-chamber igniter physics and in-cylinder performance metrics

Impact

- Better understanding of igniter physics enables predictive simulation ignition model development and provides insight on hardware/operating strategy optimization for mixed-mode combustion

FY17 Milestones

Quarter	Milestone	Status
Q1	Measure low-temperature plasma generated radicals in the optical calorimeter with representative fuel and EGR compositions.	✓
Q2	Benchmark DISI emissions and combustion performance metrics for different low-temperature plasma igniter configurations.	✓
Q3	Perform high-speed and spectroscopic imaging of low-temperature plasma igniters in the optically-accessible engine during ignition.	In Progress
Q4	Develop a suitable research engine head for turbulent jet ignition experiments.	In Progress

Approach: Remove new igniter commercialization barriers

1. <u>Concept</u>
- Solicit stakeholder input
- Establish operating principles
- Determine commercialization barriers

2. <u>Build</u>
- Create test plans to measure underlying phenomena
- Design/fabricate hardware, test platforms, & diagnostics

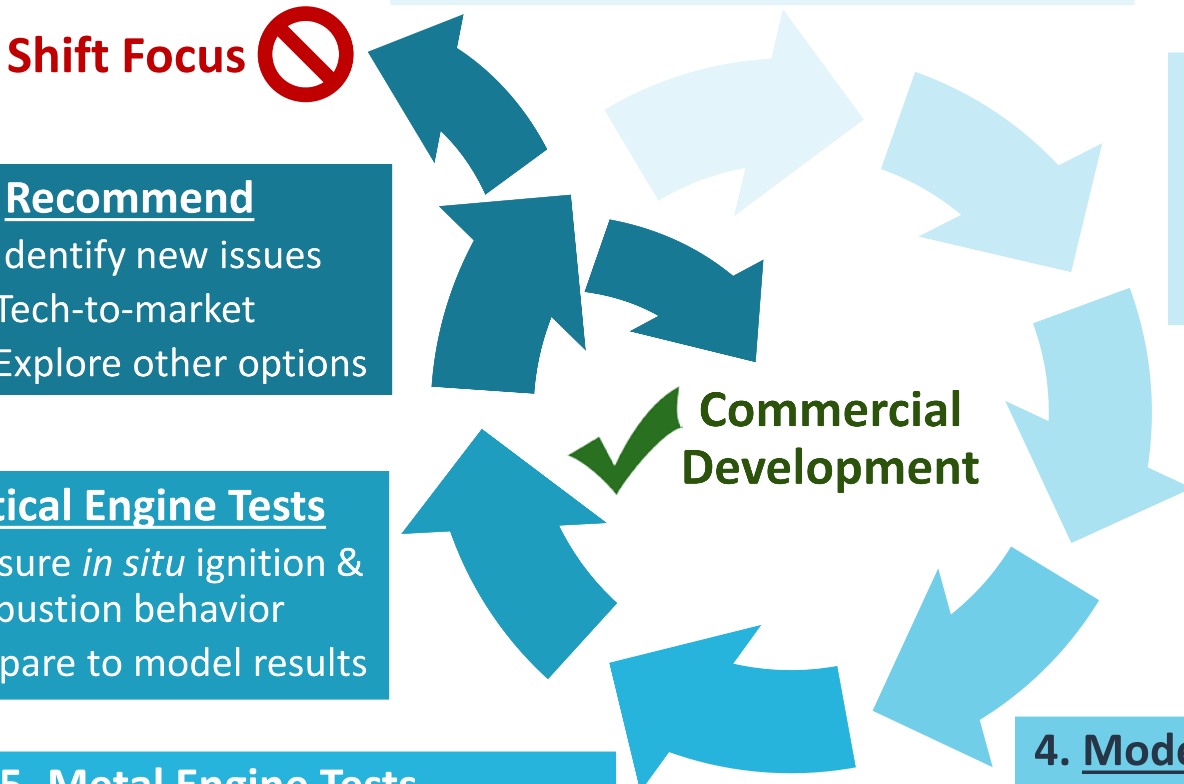
3. <u>Fundamental Tests</u>
- Conduct well-controlled experiments to probe physical processes

4. <u>Model</u>
- Develop conceptual models
- Perform full-scale simulations
- Determine modeling gaps

5. <u>Metal Engine Tests</u>
- Benchmark engine performance (e.g. emissions, CoV, ITE)

6. <u>Optical Engine Tests</u>
- Measure *in situ* ignition & combustion behavior
- Compare to model results

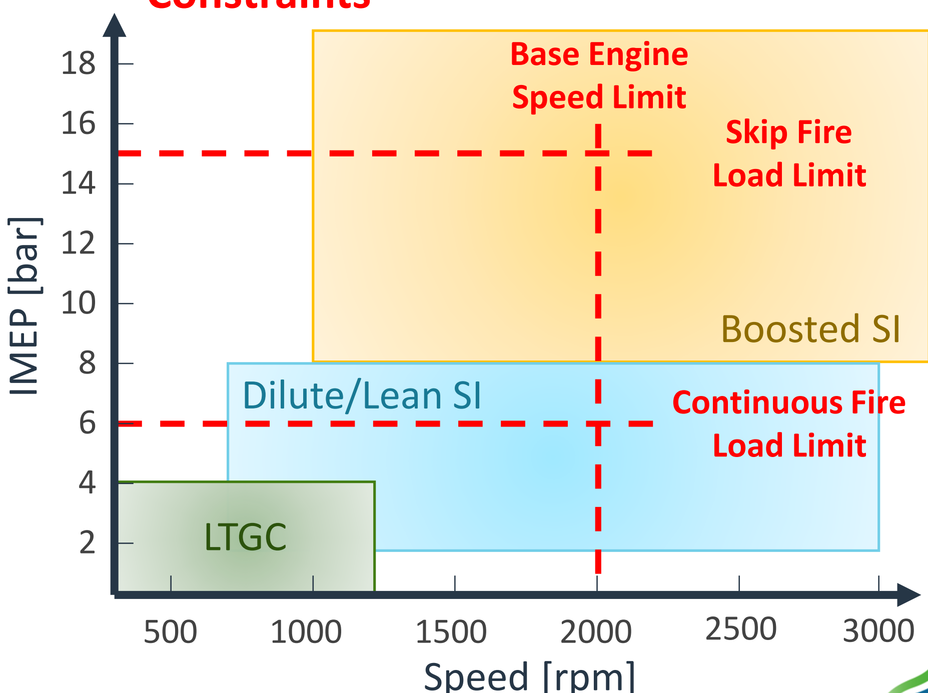
7. <u>Recommend</u>
- Identify new issues
- Tech-to-market
- Explore other options



Approach: Operating regime and test equipment

	Low-Temperature Gasoline Combustion	Un-throttled SI (lean or dilute)	Stoichiometric Boosted SI
Benefits	$\uparrow\eta_{TE}$, $\uparrow\eta_{vol}$, $\downarrow Q_{HT}$, $\downarrow T_{ad}$	$\uparrow\eta_{TE}$, $\uparrow\eta_{vol}$, $\downarrow Q_{HT}$, $\downarrow T_{ad}$	$\uparrow\eta_{mech}$, $\downarrow Q_{HT}$
Challenges	↑COV, ↑HC/CO, $\uparrow P_{peak}$, ↑dP/dt	↑COV, ↑HC/CO	$\uparrow P_{peak}$, ↑dP/dt, LSPI, Knock
Desired ignition characteristics	Chemically controlled auto-ignition centered near TDC	Multiple ignition sites with fast early flame propagation	Stable ignition with significant spark retard

Constraints



Assumptions: Variable valve lift/timing, Central DI, CR > 12

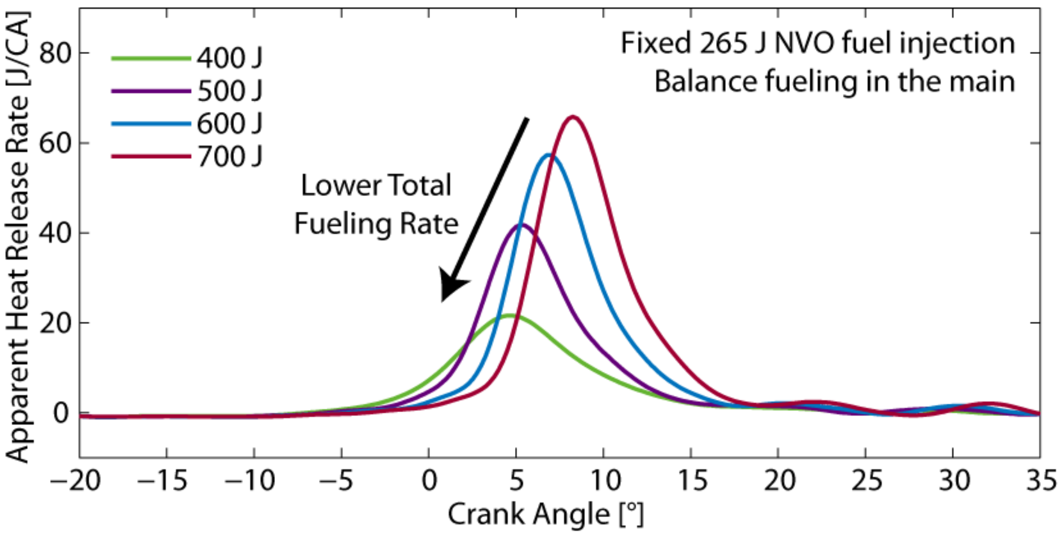
	Old Engine	New Engine		
Combustion Mode	LTGC	LTGC	Dilute SI	Boosted SI
Head design	3 valve pent-roof	4-valve pent-roof		
Igniter	None	Centrally mounted LTP		
Displacement [L]	0.63	0.55		
Stroke/Bore	1.03	1.11		
CR	11.3	13		
Intake P [bar]	1	0.8 – 1.2		1 – 2
Valve Timing	150° NVO	~34° PVO		~7° PVO

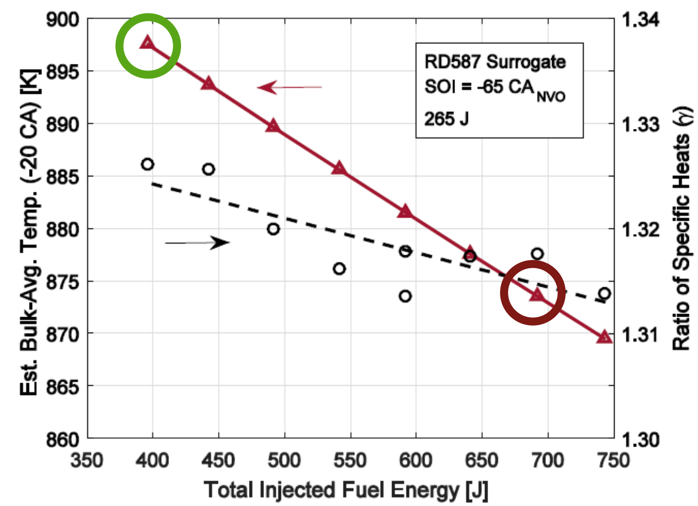
Fundamental studies: optically accessible calorimeter

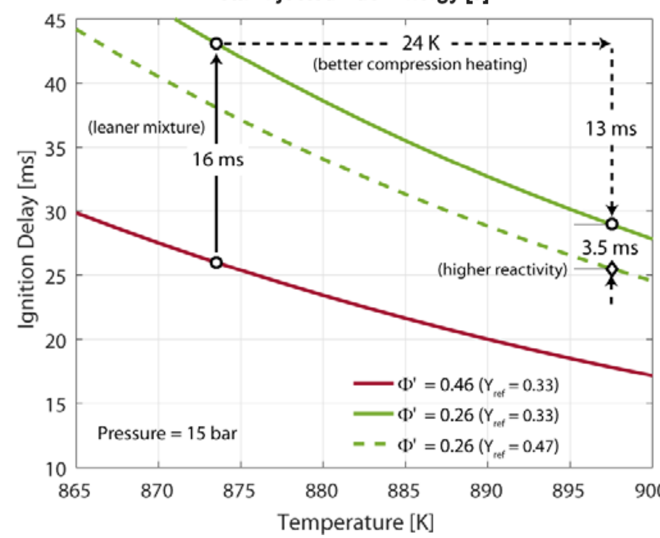
- *Gases*: O_2, N_2, CO_2, H_2O (could add NO, gaseous HC)
- *Temperature*: up to 70°C
- *Pressure*: up to 9 bar (abs.) in current config.
- *Measurable ΔP*: single-digit Pascals (29 cc chamber)
- *Other diagnostics*: imaging, schlieren, absorption, LIF

Previous: Impact of NVO reformate on LTGC auto-ignition

Ekoto et al, ASME ICEF 2016-9458







USCAR 2016 Highlight

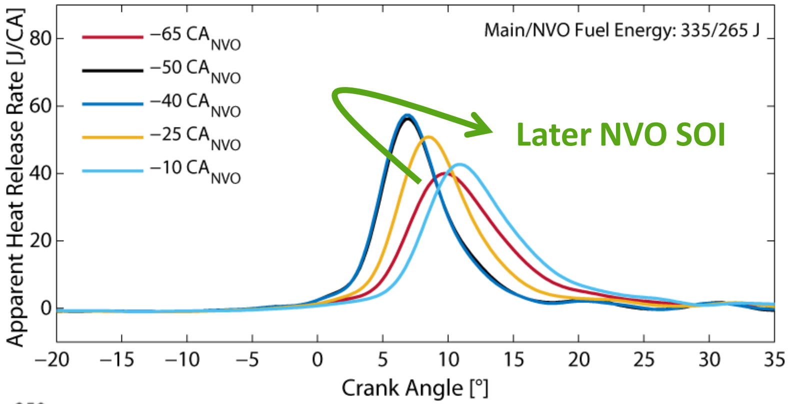
Competing effects examined via chemical modeling:

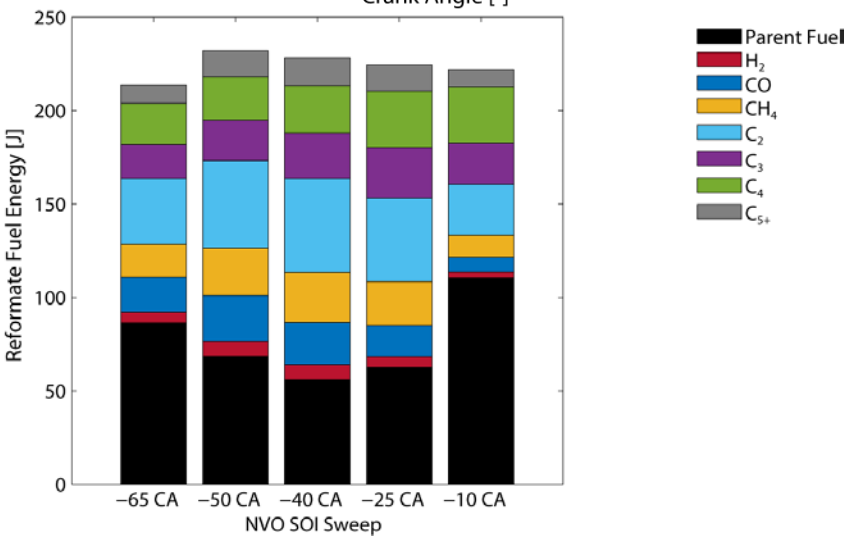
- auto-ignition retards for leaner ϕ
- **higher bulk temp.** from ↓ charge cooling & ↑ γ
- **increased reactivity** w/ ↑ reformate fraction
- species responsible for reactivity enhancement: acetylene, allene, acetaldehyde, & propene

Impact:* *Reformate addition mechanisms that accelerate auto-ignition identified

Model

Accomplishment: Impact of NVO reformate on LTGC



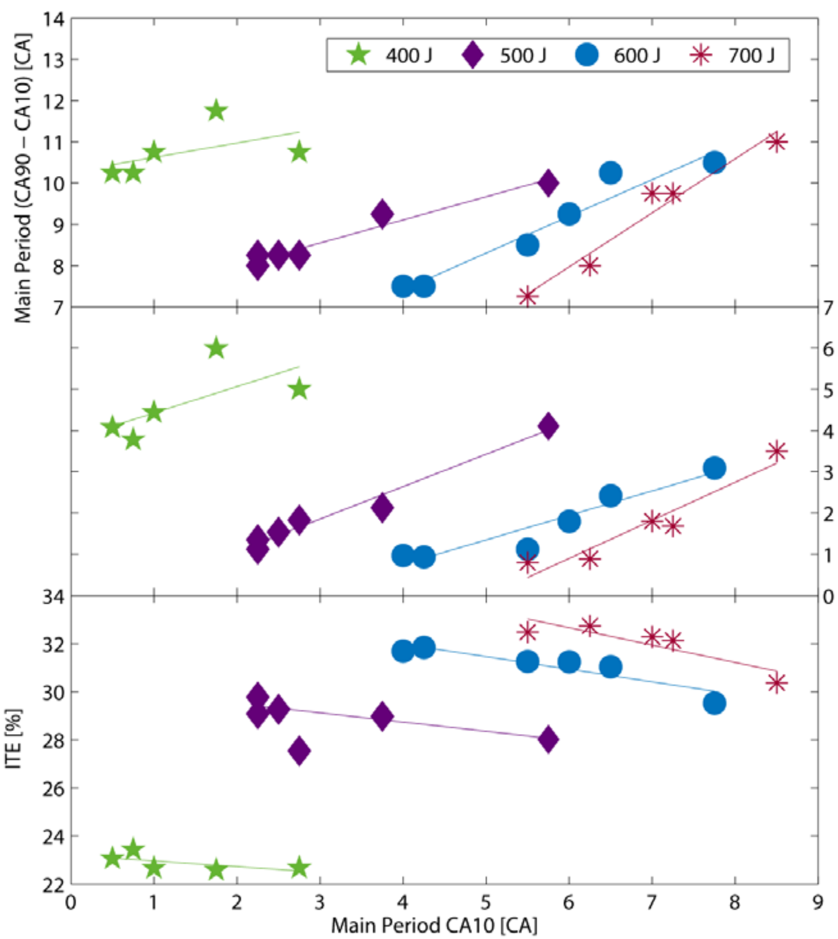


Engine Tests

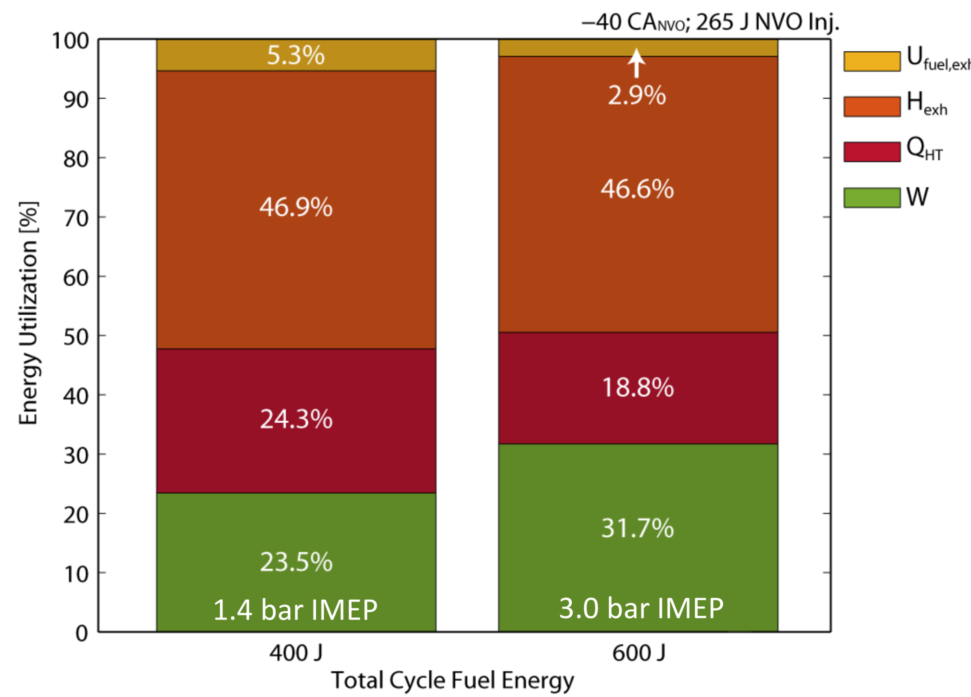
Accomplishment: Impact of NVO reformate on LTGC

For a fixed fueling rate, as CA10 retards:

- ↓ ITE
- ↑ CoV of IMEP
- ↑ Combustion Duration



Main combustion depends on ignition delays & fueling rates (i.e. not reformate composition)

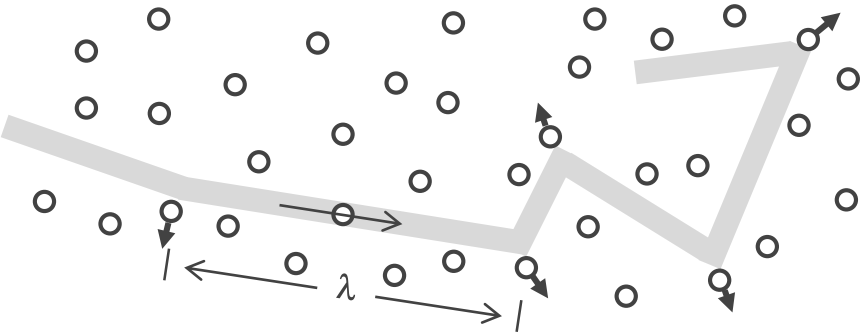


Excessive NVO-period heat loss (4-6%)

Impact: Combustion optimally phased by altered reactivity, but heat losses are prohibitive.

Shift Focus

Previous: LTP igniter selection

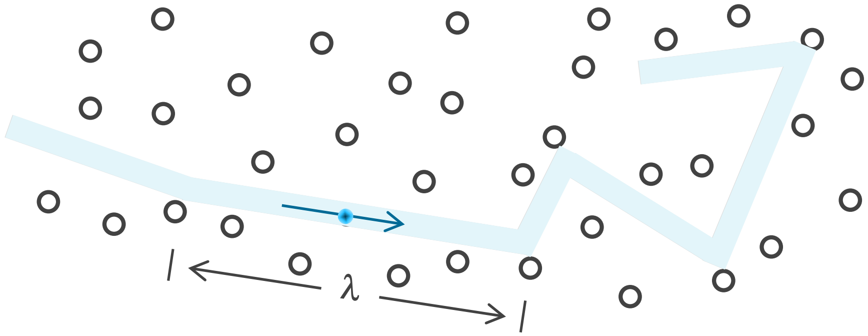


Parameters

Mean free path: $\lambda \propto 1/N \propto T/P$

Concept

Previous: LTP igniter selection



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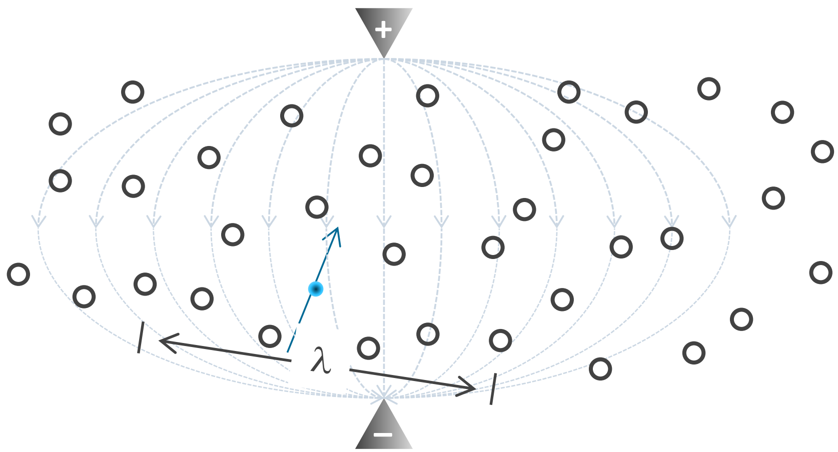


Parameters

Mean free path: $\lambda \propto 1/N \propto T/P$

Electric field : $|E| \propto$ electron acceleration

Reduced electric field: $|E|/N \propto$ electron energy

Plasma Classification

Thermal: <u>Elastic</u> energy transfer $\Rightarrow \mathrm{T_e} \approx \mathrm{T_{gas}}$

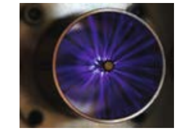
Non-thermal: <u>Electron</u> energy transfer $\Rightarrow T_e \gg T_{gas}$

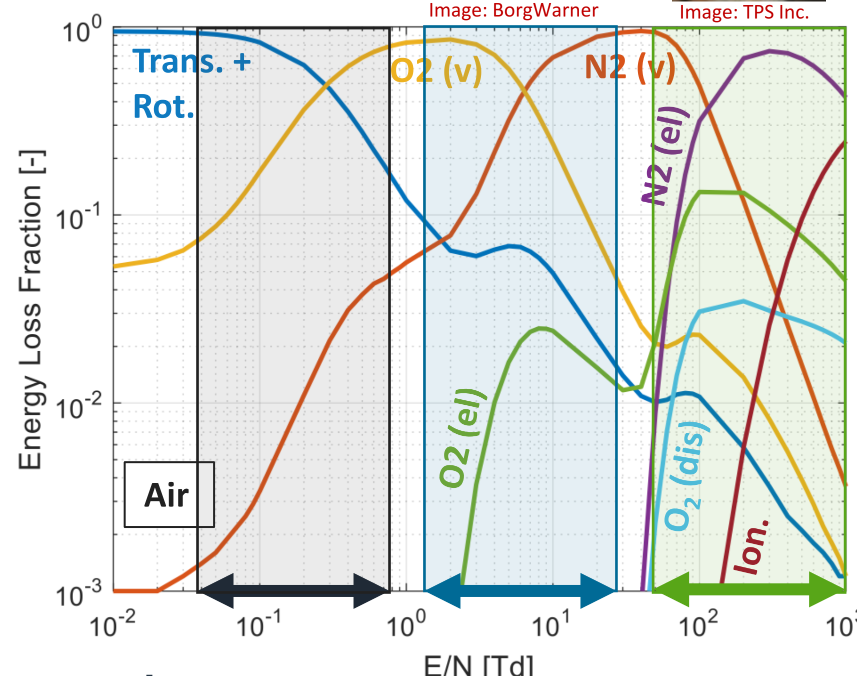
Electron energy transfer mechanisms

Vibrational-to-translational relaxation: **slow**

Electronic gas heating: **fast**

Chemical ionization/dissociation: **fast**

Inductive Spark	RF Corona	Nanosecond Discharge
		
Image: NGK	Image: BorgWarner	Image: TPS Inc.



Ignition Mechanism	Thermal heating	Thermal & non-thermal heating	Non-thermal heating & radicals

LTGC:
- Early ozone generation to promote auto-ignition

Dilute SI:
- Volumetric gas heating
- Local O & H formation

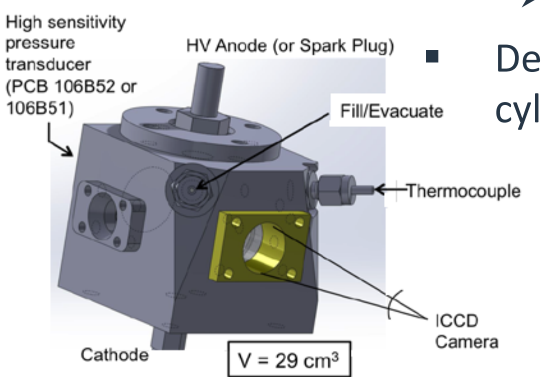
Boosted SI:
- Fast turbulent flame kernel development

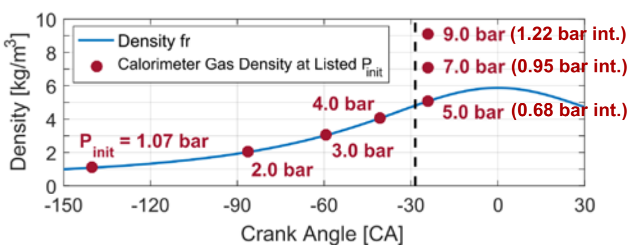
Concept

Accomplishment: Physical LTP experiments

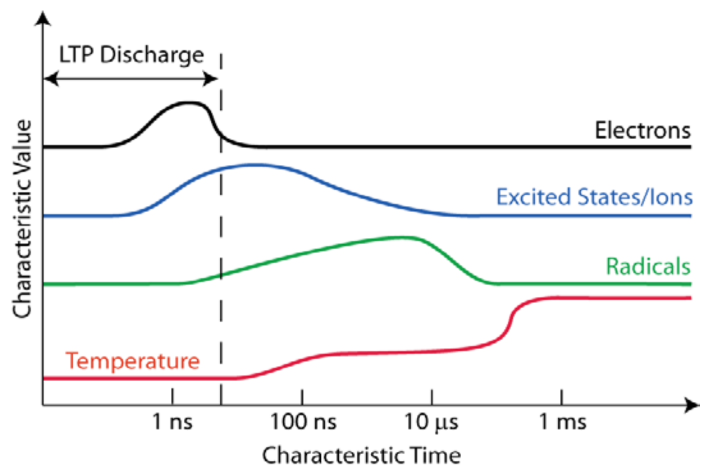
- High-voltage (28 kV) short duration (10 ns) pulses
- Canonical electrode geometries
  - Non-resistor spark plug
  - Ground removed & anode sharpened
  - Opposing sharpened cathode
  - Anode-only configuration also explored
- Density/composition matched to Argonne single-cylinder engine tests at lean & dilution limit MBT

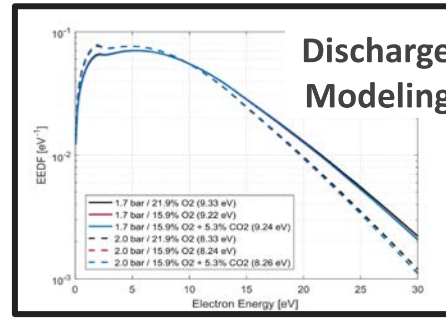
Optically-Accessible Spark Calorimeter

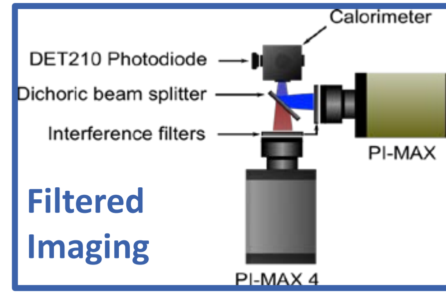


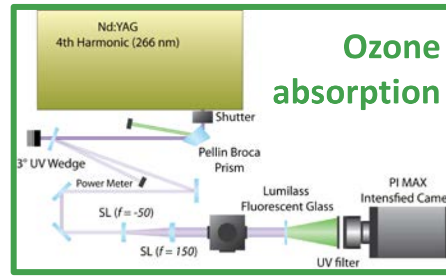


Sevik et al, ASME ICEF (2016)

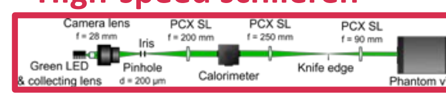








High-speed schlieren



Pressure rise calorimetry

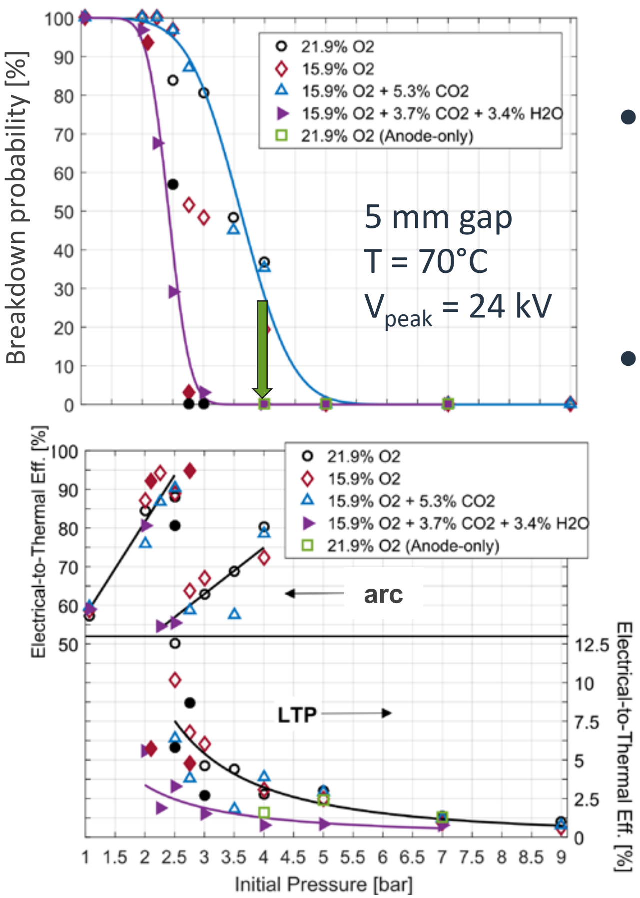
- Arc Transition Probability
- Pulse Energy
- Electrical-to-Thermal Energy

Impact: Apparatus enables fundamental measurements of discharge phenomena in a well-controlled environment.

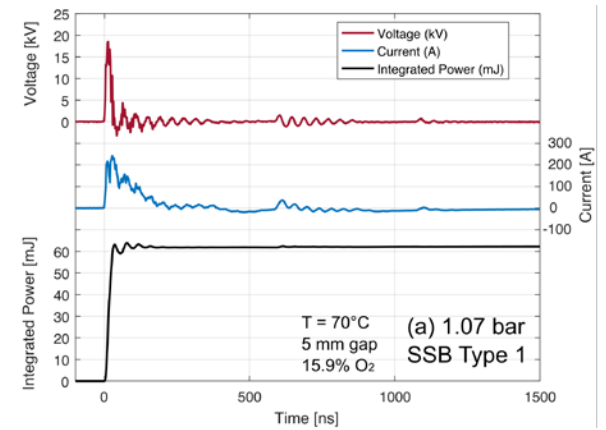
Build

Accomplishment: Arc transition limits identified

Note: solid symbols from a different ultra air bottle



- Minimal impact of gas composition on arc probability
- Anode-only configuration lowers the breakdown limit
  - Apparent arcs along the insulator occur at low densities
- Large reduction in breakdown transition density w/ added H_2O (coincided w/ a changed in ultra-air bottle)
  - Could be lower argon content (no spec. for ultra zero air)
  - We have switched to desiccated house air
- Very efficient electric-to-thermal energy transfer during arc



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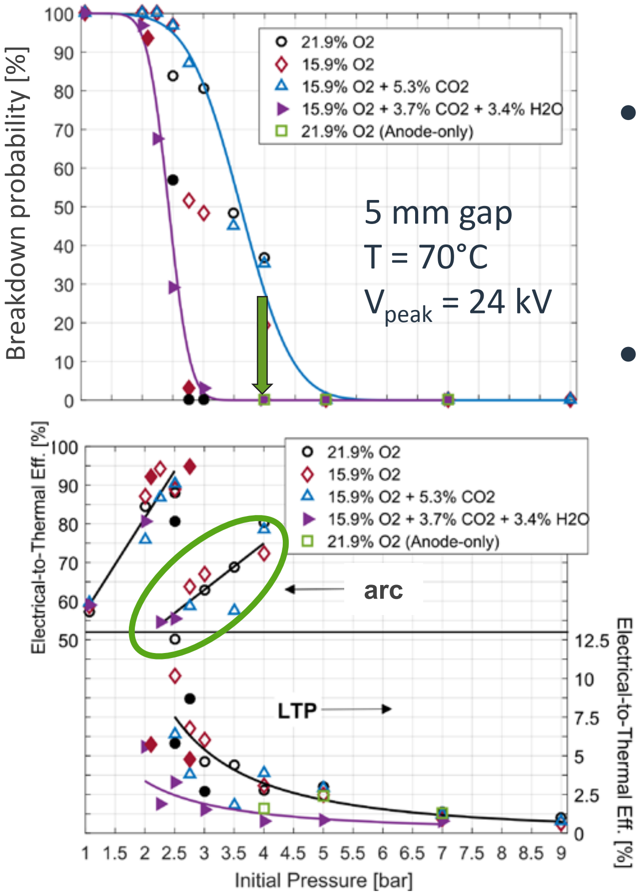

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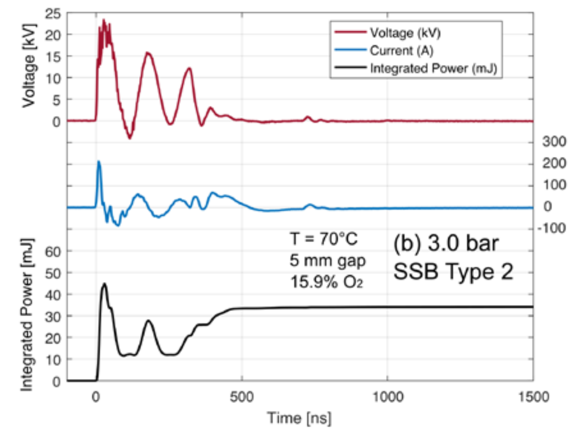

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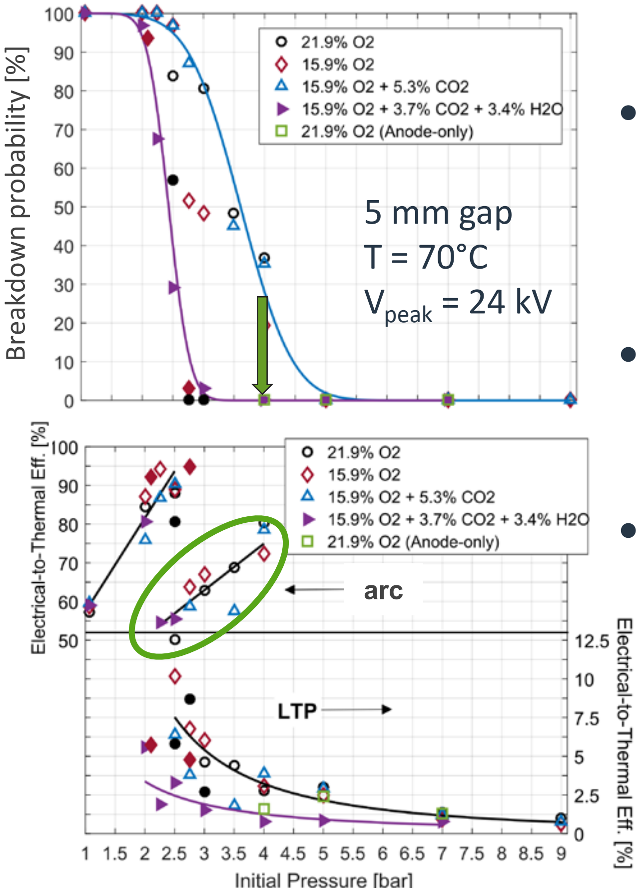

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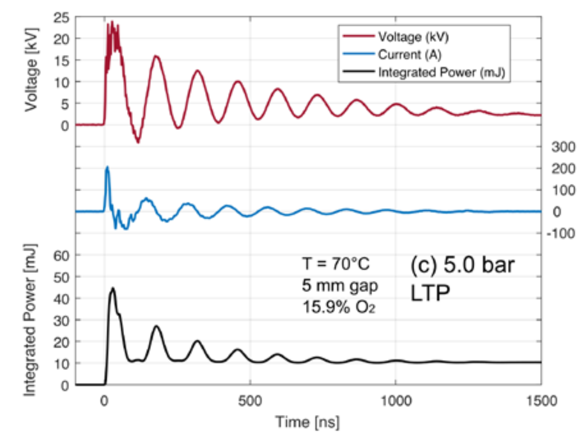
  - Could be lower argon content (no spec. for ultra zero air)
  - We have switched to desiccated house air
- Very efficient electric-to-thermal energy transfer during arc
  - Delayed arc due to pulse voltage/current oscillations
- Lower electric-to-thermal energy transfer for LTP
  - Exponential decay in energy transfer w/ increased density
  - Heating still comparable to inductive coil systems

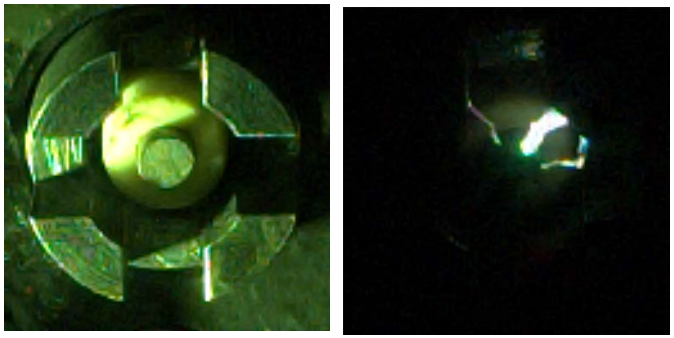


Upshot: **CO_2 & H_2O addition to not influence occurrence of arc.**

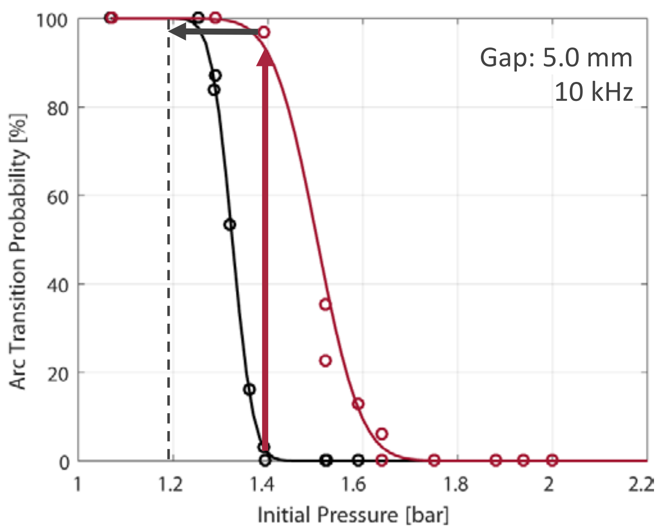
Basic Tests

Accomplishment: Multi-pulse arc transition explained

Sjöberg et al, *SAE Int J Engines*, 2014



Arcs with multi-pulse – no arc with single-pulse
$\Longrightarrow$ a thermal or chemical pre-conditioning mechanism



Wolk & Ekoto, IAV Conference on Ignition Systems, 2016.

Engine results confirmed by calorimetry

Calorimetry

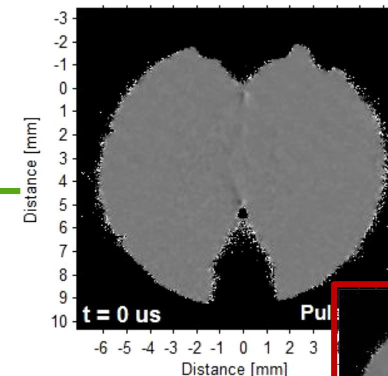
$$\Delta T = \frac{\boxed{E_{Thermal}}}{\rho c_p \boxed{V}}$$

Assumed cylinder

Thermal model developed

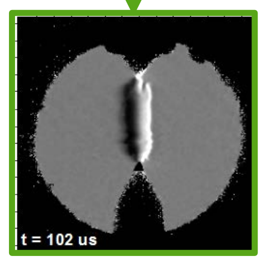
Minimal heat transfer between pulses

- +15% temp. @ 2^nd pulse
- predicted arc probability: 100%



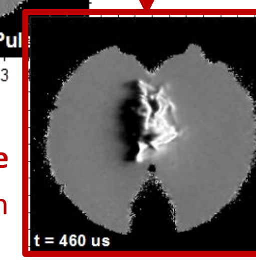
Inductive Spark

Laminar expansion



Nanosecond Discharge

Turbulent expansion



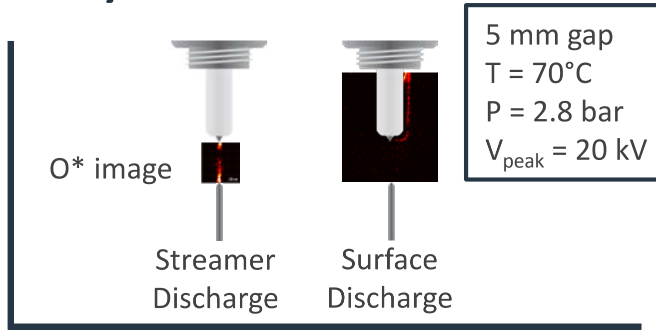
Impact: **Extended dilution limits with nanosecond discharges attributed to arc-induced faster kernel growth rates – not LTP physics.**

→ ***<u>Better pulse & electrode optimization needed for true LTP ignition</u>***

Recommend

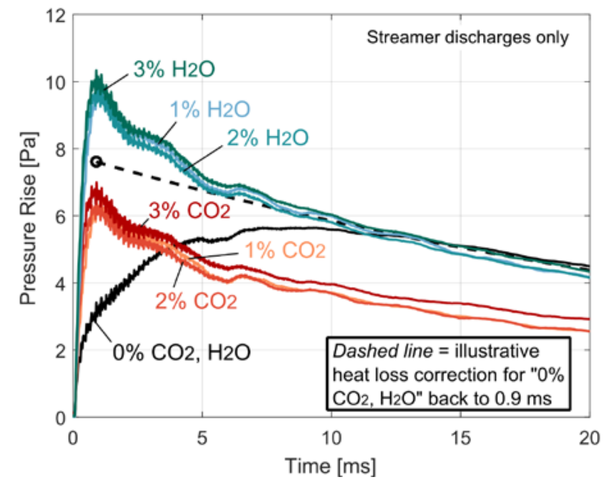
Accomplishment: Unique with CO_2/H_2O dynamics observed

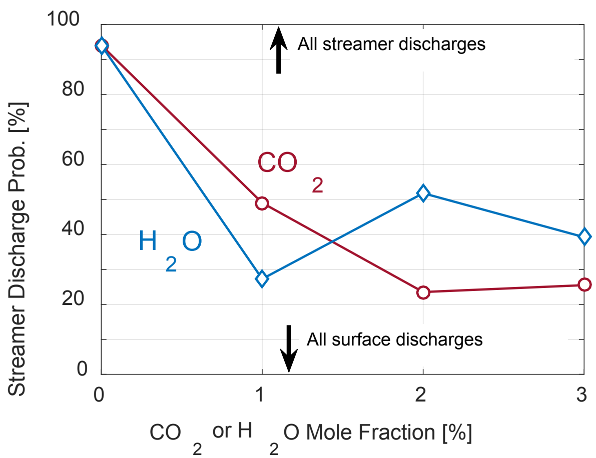
- Surface discharges observed along the ceramic insulator above threshold pressure
  - Undesirable: poor heating & radical production



CO_2 and H_2O addition impacts discharge characteristics

Positive : Sharper pressure-rise for streamer-only discharges indicates improved heating





Negative : Surface discharge probability increases with increased CO_2 or H_2O content

- Surface discharge propensity is sensitive to insulator design

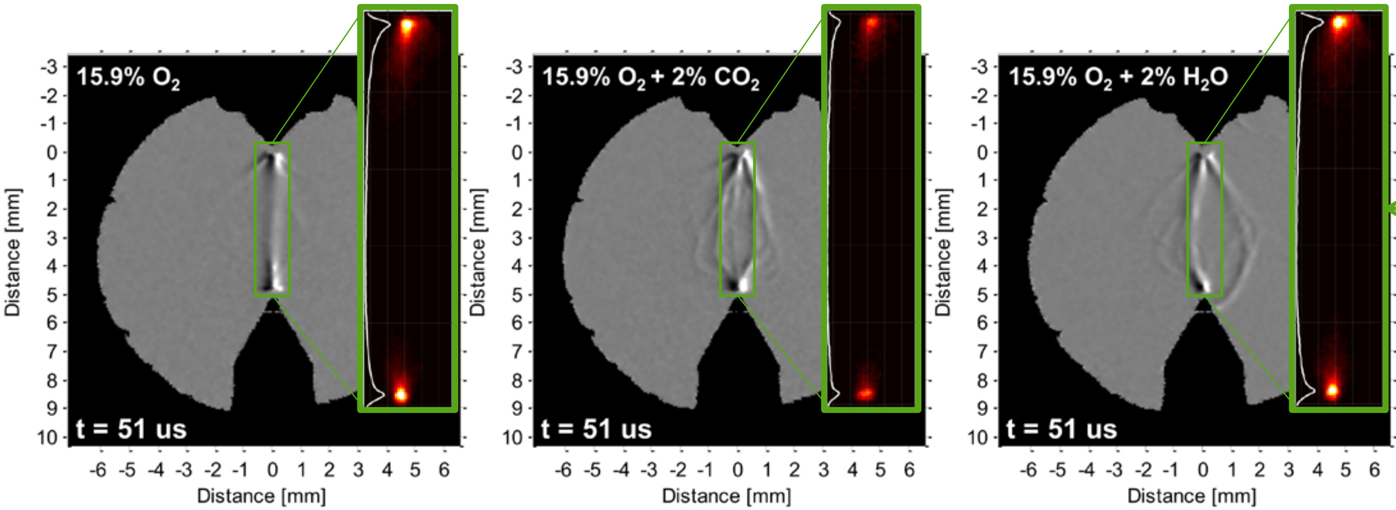
Upshot: **Unknown chemical dynamics from CO_2 & H_2O addition impact streamer behavior.**

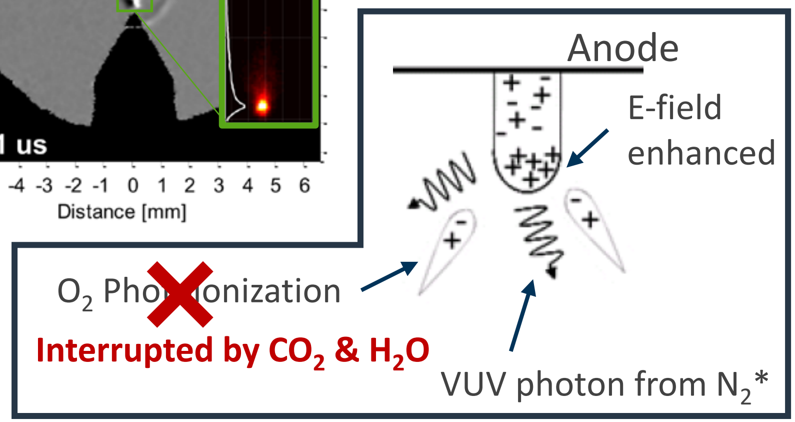
Accomplishment: Unique dynamics with CO_2/H_2O explained

5 mm gap
T = 70°C
P = 2.8 bar
V_{peak} = 20 kV

- CO_2 and H_2O addition both lead to increased streamer branching
  - Improved heating due to:

    more branching → thin streamers → fast cooling → fast V-T relaxation





- Decreased O* formation with CO_2 addition
  - Not from changes in quenching, chemistry, or fluorescence trapping (see technical backup slides)
  - Likely from less E-field enhancement due to more efficient VUV CO_2 & H_2O absorption relative to O_2
  - **Not a feature of RF corona LTP due to the absence of VUV photons!**

Impact: **Unique nanosecond discharge streamer physics with CO_2 and H_2O addition identified.**

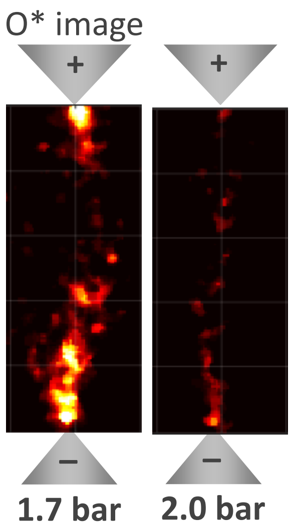
Basic Tests

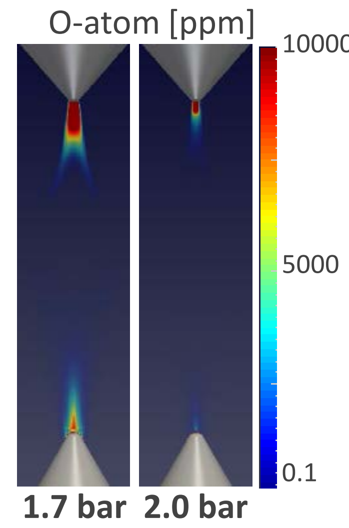
Accomplishment: LTP experiments & modeling comparison

- Substantial O* observed for air nanosecond discharges

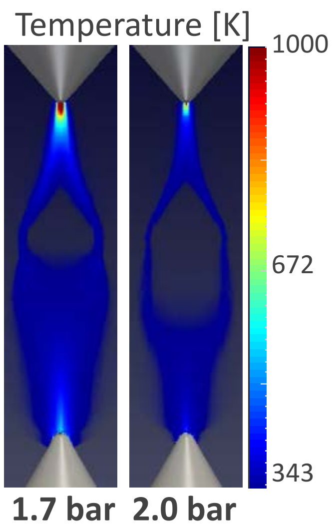
  O(3p³P → 3s³S) transition at 844.9 nm

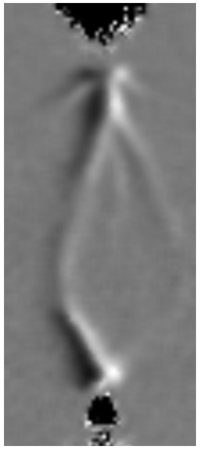
  – Due to high-energy electrons – <u>not present w/ RF corona</u>
  – Highest signal near electrodes where E-field is strongest
  – Rapid signal decrease w/ higher pressure due to lower E/N
- Argonne simulations show similar O-atom distributions
  – VizGlow: high-fidelity non-equilibrium plasma code that accounts for bulk-gas heating & photoionization effects





Simulation results courtesy of
Riccardo Scarcelli
Argonne National Laboratory





- Simulation temperature distributions also qualitatively agree with post-discharge schlieren images

Impact: **Complementary simulation & experiment capabilities enable systematic investigations into:**

1) the cause of surface discharges
2) best electrode configurations
3) optimal pulsing strategies

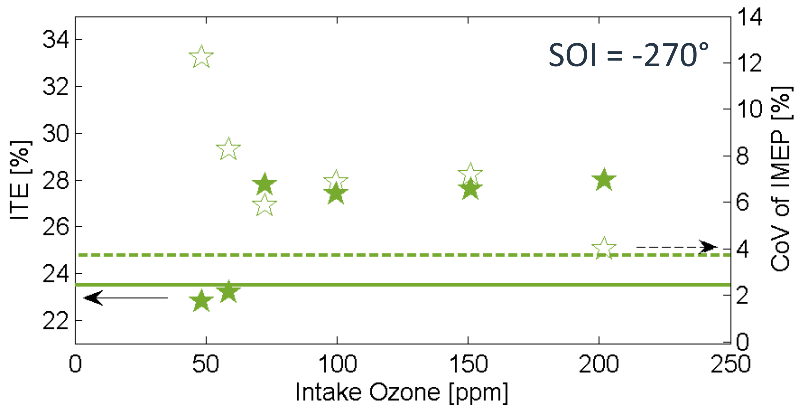
Model

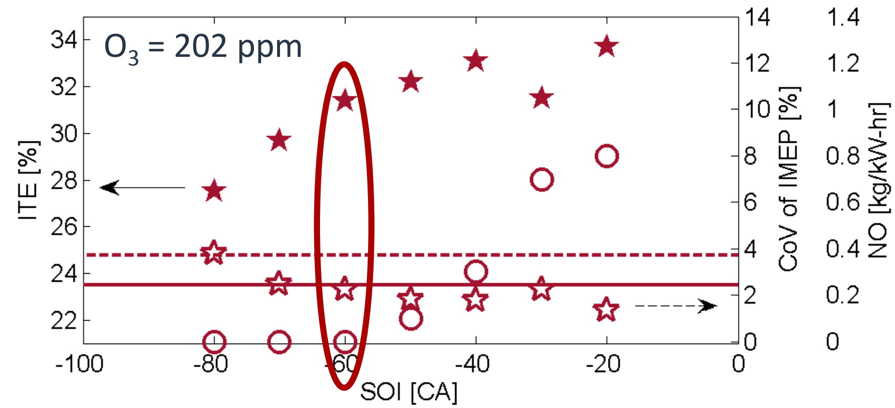
Accomplishment: Characterization of O_3 on near-idle LTGC

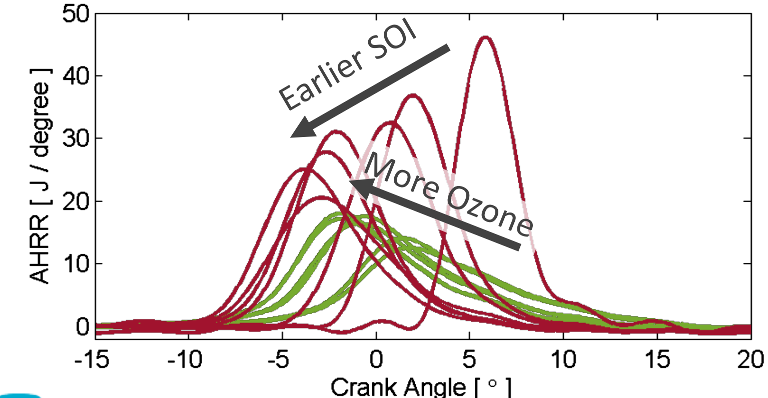
Speed: 1000 rpm
Fuel: 6.2 mg/cycle (PRF 80)
Load: ~1.5 bar IMEP
P_{intake}: 90 kPa
T_{intake}: 155 K

Controlled ozone concentrations seeded into the intake

- Goal: Benchmark engine performance with known quantities of O_3
  - Will inform Q3 study where O_3 is formed by the LTP discharge
- ~80 ppm O_3 increases ITE ~5 points relative to a similar NVO condition
  - Accelerated low-temperature chemistry advances combustion phasing







- Further increase in ITE with DI retard
  - NO emissions rise for SOI retard beyond -50°aTDC

Impact: **Approx. 8 point ITE improvement relative to the best NVO operating point with virtually no NOx using ozone.**

Engine Tests

Reviewer Response

Q1: Is the purpose of the ignition work to establish conditions for auto-ignition or initiate combustion.

Response: We believe advanced ignition systems can switch between auto-ignition promotion for LTGC and flame propagation initiation for more conventional SI combustion on a cycle-resolved basis. Particular emphasis this year has been on nanosecond discharge LTP where non-thermal heating and radical production pathways can influence either mode of operation. Similar investigations for jet igniters are planned next year.

Q2: Good explanation of observed effects of reformate addition, but progress continues to be slow.

Response: A complete engine test-cell revamp along with the development of suitable optical diagnostics and complementary test vessels was required to properly address open questions about relevant advanced ignition systems. Now that these activities are mostly complete, research output related to advanced ignition systems has increased substantially.

Q3: More OEM ignition system collaboration would help provide project guidance & industry feedback.

Response: This past year we have reached out to various OEMs regarding collaborative ignition system testing and have also solicited project feedback. Most OEMs have provided guidance through intermittent video-conferences, phone calls, or informal conversations. We have a more active collaboration with GM R&D (that include shared hardware development) on turbulent jet ignition systems.

Q5: Improved understanding of ignition systems and processes in gasoline engines is critical to improving engine efficiency.

Response: We agree that new ignition systems enable more robust methods of operation that are not possible with more conventional ignition systems. The challenge continues to be devising high-value experiments that elucidate fundamental mechanisms so that these systems can be properly optimized.

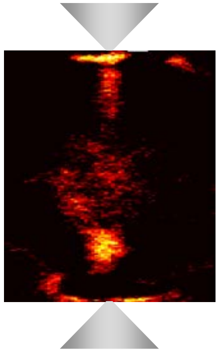
Collaborations

- National Lab
  - Argonne National Lab (Riccardo Scarcelli & James Sevik):
    - Shared validation data in support of advanced ignition modeling
  - Sandia FES (Ed Barnat & Matthew Hopkins):
    - Shared results and advice on LTP discharge modeling and experiments
- University
  - U. Orléans (Prof. Fabrice Foucher):
    - 3-month sabbatical by Prof. Fabrice Foucher to perform joint experiments into ozone formation by LTP discharges
  - Michigan State (Profs. Harold Schock & Elisa Toulson):
    - Joint jet ignition experiments with a common single-cylinder research head (w/ GM R&D)
  - U. Minnesota (Prof. William Northrop):
    - Assistance with in-cylinder reformate sampling
    - Reactor modeling of the reforming cycles
- Automotive OEM and Suppliers
  - GM R&D:
    - Regular technical interactions: 1) results exchange, 2) hardware support, & 3) feedback on research directions
    - Joint jet ignition experiments with a common single-cylinder research head (w/ Mich. State)
  - Ford, FCA, Cummings:
    - Intermittent technical discussion on LTP ignition: 1) results exchange & 2) feedback on research directions
  - Mahle GmbH:
    - Collaborative research on the mechanisms of ignition for jet ignition
    - Mahle to provide hardware loans as needed
- Small business
  - Transient Plasma Systems Inc.:
    - Data and hardware sharing
    - Electronics design and maintenance support for high-voltage nanosecond pulse generators
- DOE Working Group
  - Share research results and insights at the DOE's Advanced Engine Combustion working group meetings.

Remaining Challenges and Barriers

- **LTP igniter design**: What are the optimal LTP igniter characteristics?
  - Is the cathode needed, or is an anode-only configuration sufficient?
  - Are higher voltages needed?
  - Can multi-pulse operation be used to increase heating while avoiding arc?
  - How can surface discharges be avoided? Insulator re-design?
- **In-cylinder ozone generation**: Can LTP generated O_3 favorably influence LTGC auto-ignition?
  - Can O_3 eliminate the need for intake pre-heating at very low loads?
  - What is the impact of added CO_2? Does this reduce O_3 formation rates?
  - Can multi-pulse be leveraged to increase radical yields?
- **Streamer initiated flame propagation**: Can nanosecond LTP non-thermal heating and radical production lead to extended dilution limits?
  - How do altered CO_2 and H_2O streamer dynamics influence ignition? What about fuel?
  - Is there an in-cylinder density limitation?
- **Jet Ignition**: What is the mechanisms for ignition?
  - What is the interplay of flow (i.e., mixing) and chemistry on ignition?
  - How sensitive are ignition characteristics to what goes on in the pre-chamber?

Preliminary O_3 absorption image



Future Work

Any proposed future work is subject to change based on funding levels

- **<u>LTP igniter design</u>:**
  - Coat portions of electrode with high-dielectric strength epoxy to inhibit arc: **Q3FY17**
  - Evaluate new TPS Inc. pulse generator capable of 50 kV_{peak}: **Q4FY17**
  - Identify supplier partners that can develop custom electrodes (i.e., insulators): **FY18**
- **<u>In-cylinder ozone generation</u>:**
  - Measure LTP generated O_3 concentration in the calorimeter via laser absorption: **Q3FY17**
  - Determine lowest intake temperature limit for stable low-load LTGC using O_3: **Q3-Q4FY17**
  - Explore impact of early-LTP on LTGC auto-ignition through O_3 formation: **Q3FY17-Q2FY18**
- **<u>Streamer initiated flame propagation</u>:**
  - Perform additional LTP calorimetry and spectroscopic measurements with fuel, CO_2, and H_2O containing air mixtures: **Q3-Q4FY17 – Summer intern project**
  - Explore impact of late-LTP on SI lean/dilute limits (w/ and w/o cathode): **Q3FY17-Q2FY18**
  - With modelers, evaluate fast-gas heating & photoionization mechanisms: **Q3FY17-FY18**
  - Find boosted SI operability limits with LTP: **Q4FY18**
- **<u>Jet Ignition</u>:**
  - Assemble engine optimized for jet ignition: **Q3FY18**
  - Visualize the chemical and mixing field at the jet head where ignition occurs**: FY18**

Summary

Relevance

- Explore how advanced ignition systems can facilitate efficient, mixed-mode combustion across the load/speed map: i.e., low-load LTGC, moderate-load dilute SI, and high-load boosted SI.

Approach

- Remove new igniter commercialization barriers through targeted engine and optical calorimetry experiments, with complementary modeling performed by national lab partners

Technical Accomplishments

- In-cylinder generated reformate can optimally phase LTGC auto-ignition through altered fuel reactivity characteristics – Parasitic heat loss penalty (4 – 6% of the fuel energy) makes this strategy prohibitive
- Arc transition probability mapped for nanosecond discharges at engine relevant densities for mixtures of air, CO_2, and H_2O using canonical pin-to-pin electrodes
- CO_2 and H_2O found accelerate bulk-gas heating due to thinner streamers, but increased the propensity for surface discharges due to interrupted photoionization processes
- Argonne simulations (VizGlow) found to qualitatively agree with discharge imaging
- Thermal arc transition mechanism for multi-pulse nanosecond discharge operation identified
- ~80 ppm of O_3 addition found to effectively phase LTGC auto-ignition and led to an ~8 point improvement in ITE relative to NVO operation due to a reduction in heat losses

Proposed Future Research

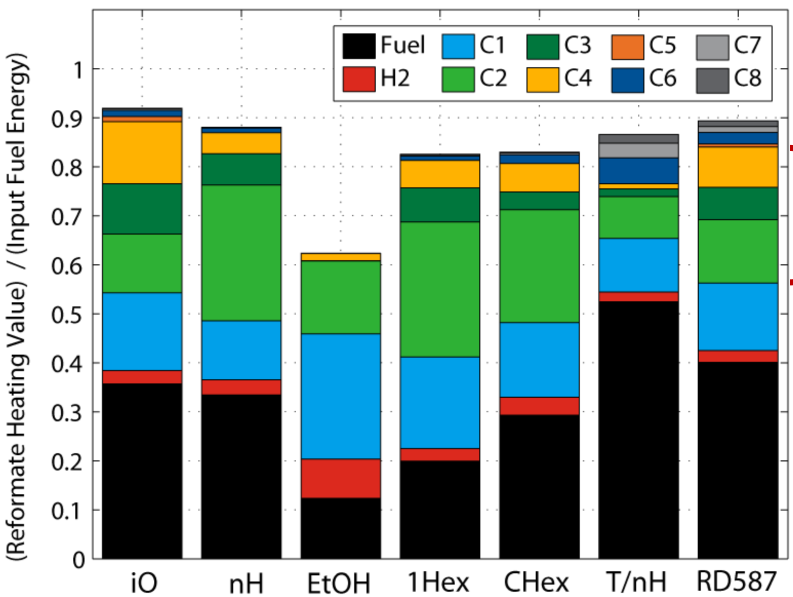
- Optimize LTP discharge igniter geometry
- Experimentally explore in-cylinder O_3 production via LTP on LTGC
- Measure streamer dynamics in the optical spark calorimeter and evaluate LTP on lean/dilute SI
- Build and test engine outfitted with a jet igniter

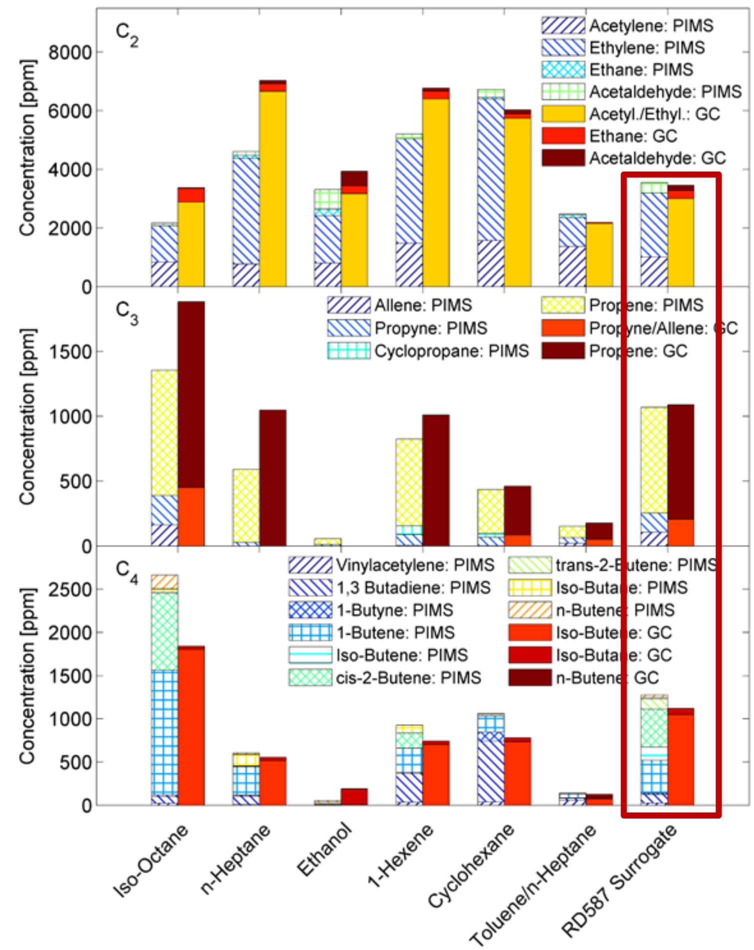
Any proposed future work is subject to change based on funding levels

Technical Backup Slides

Technical Backup Slide: Reformate Constituents

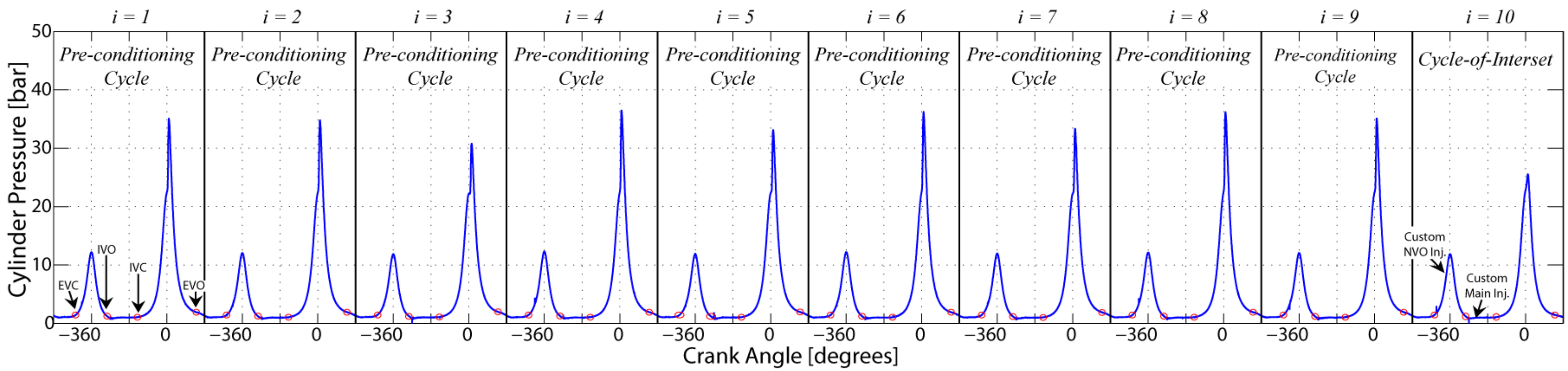
- **GC**: characterize fuel energy breakdown
  - ~90% fuel energy recovery (~60% for ethanol)
  - most energy from parent fuel, CO, H_2, & small HC
- **PIMS**: find species that influence auto-ignition
  - higher fidelity speciation relative to GC results





Impact: ***Results enable a systematic evaluation into the importance of each constituent on auto-ignition chemistry via kinetic modeling.***

Technical Backup Slide: Alternate-fire cycle energy model



Woschni correlation

$$\int hA(T - T_w)dt$$

Includes retained exhaust enthalpy & fuel

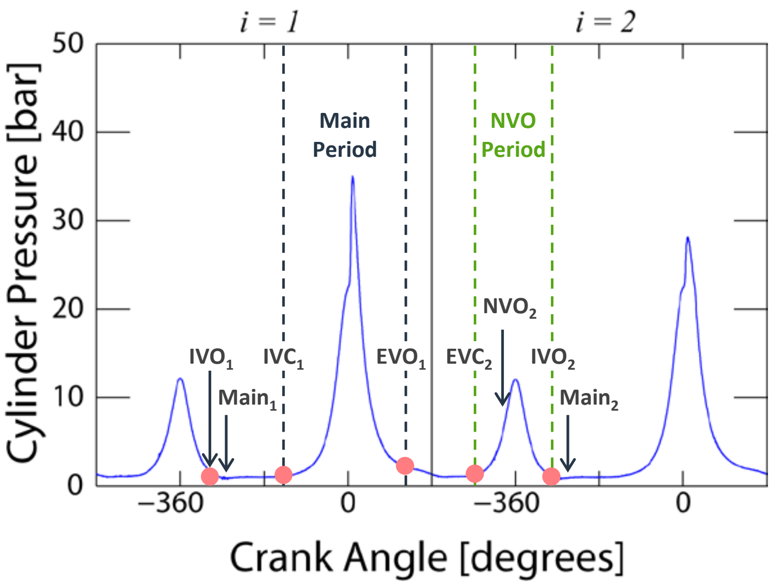
Unsteady exhaust composition limits direct measurement

$$\boxed{U_{input_i}} = \boxed{W_i} + \boxed{Q_{HT_i}} + \boxed{H_{EVO_i}} + \boxed{U_{fuel,EVO_i}}$$

$$\int PdV \qquad f(m_{EVO}, T_{EVO}, \chi_{EVO})$$

Solving each term requires estimates of the: (1) residual gas fraction, (2) composition at each valve event & (3) bulk-gas temperature

Technical Backup Slide: Alternate-fire cycle energy model

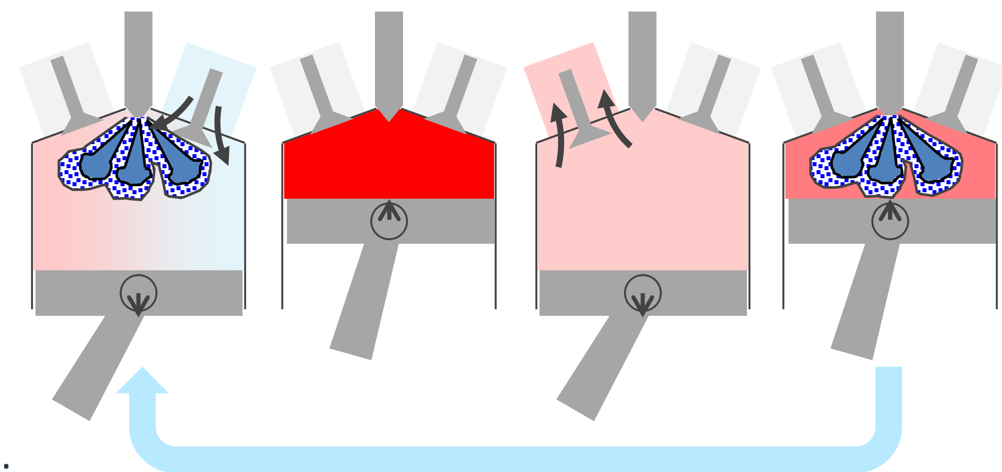


1. $RGF_i \equiv \dfrac{\sum_j m_{NVO,out_{i,j}}}{\sum_j m_{main,out_{i-1,j}}}$
2. $\sum_j m_{main,in_{i-1,j}} = \sum_j m_{int_j} + \sum_j m_{NVO,out_{i-1,j}}$
3. $\boxed{\sum_j m_{main,out_{i-1,j}} = \sum_j m_{main,in_{i-1,j}} + m_{main_{i-1,fuel}}}$
4. $\sum_j m_{exh_{i-1,j}} = \sum_j m_{int_j} + m_{main_{i-1,fuel}} + m_{NVO_{i-1,fuel}}$
5. $\sum_j m_{NVO,in_{i,j}} = \sum_j m_{main,out_{i-1,j}} - \sum_j m_{exh_{i-1,j}}$
6. $\boxed{\sum_j m_{NVO,out_{i,j}} = \sum_j m_{NVO,in_{i,j}} + m_{NVO_{i,fuel}}}$

Composition out of Main and NVO-periods

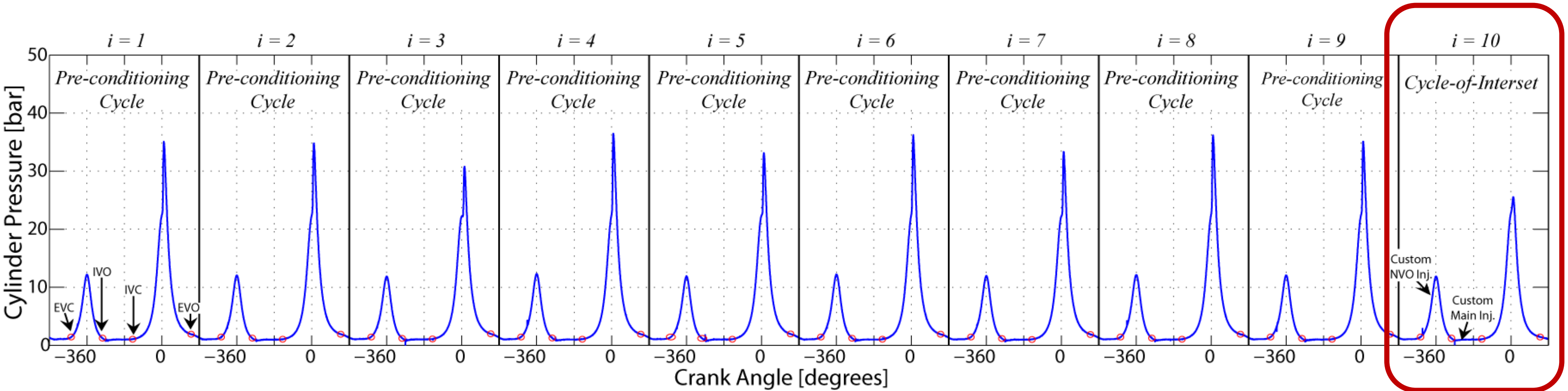
- 6 species considered: j = N_2, O_2, CO_2, H_2O, CO, fuel
  - 4 atom balance eqns. for each NVO & main period
- **Closed Main period** assumptions:
  - All fuel consumed (globally lean)
  - 95% of fuel carbon to CO_2; 5% to CO
- **Closed NVO period** assumptions:
  - All O_2 consumed (globally rich)
  - 90% of fuel carbon converted to CO; 10% stays as fuel

Bulk-temp. solved using trapped mass & cyl. press.



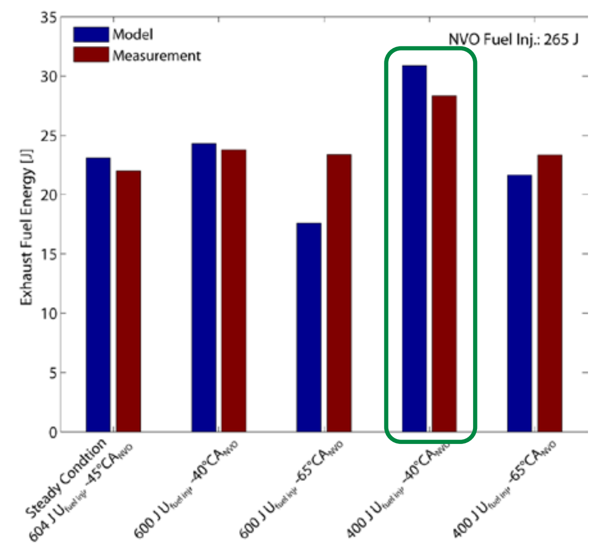
CRF

Technical Backup Slide: Alternate-fire cycle energy model

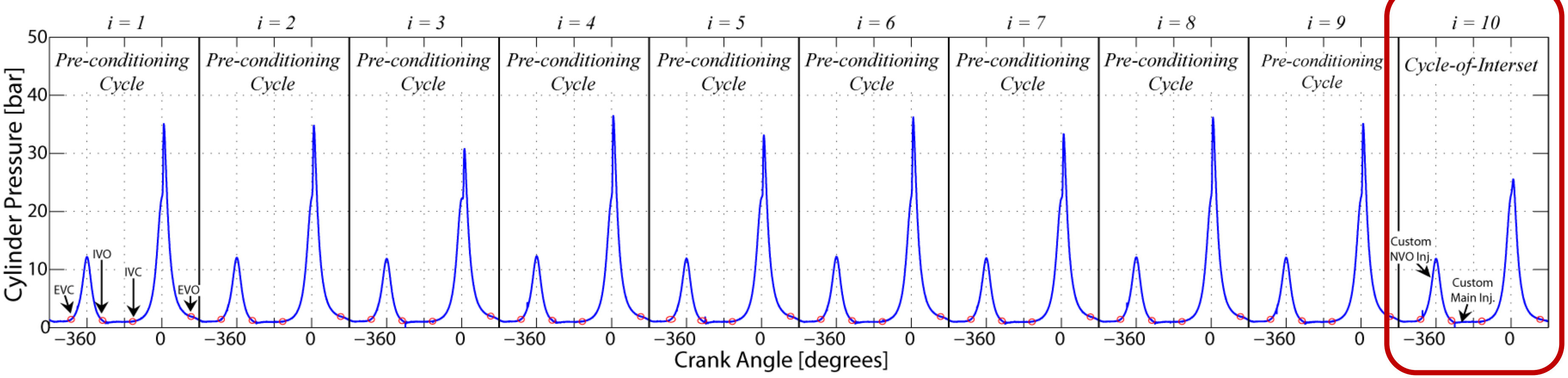


$$U_{input_i} \equiv U_{fuel\,inj_i} + \left(H + U_{fuel}\right)_{EVC_i} - \left(H + U_{fuel}\right)_{EVC_{i+1}} = W_i + Q_{HT_i} + H_{exh_i} + U_{fuel,exh_i}$$

- Model exhaust fuel energy values compare favorably to dump-sample measurements

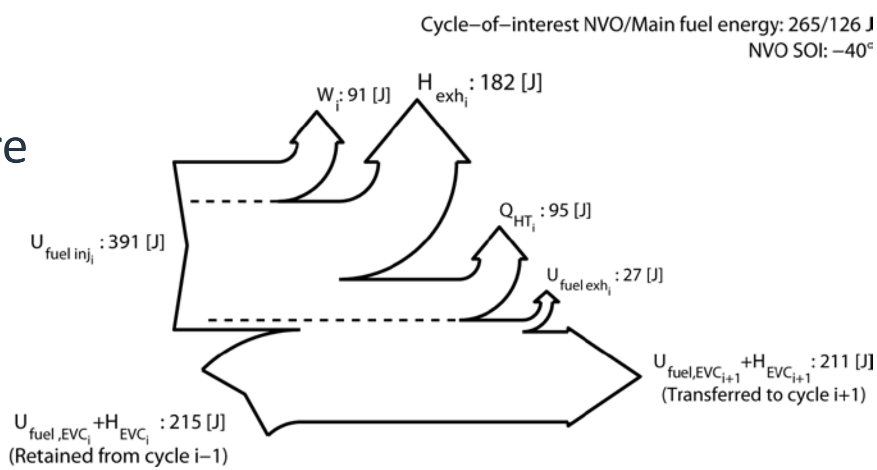


Technical Backup Slide: Alternate-fire cycle energy model



$$U_{input_i} \equiv U_{fuel\,inj_i} + \left(H + U_{fuel}\right)_{EVC_i} - \left(H + U_{fuel}\right)_{EVC_{i+1}} = W_i + Q_{HT_i} + H_{exh_i} + U_{fuel,exh_i}$$

- Model exhaust fuel energy values compare favorably to dump-sample measurements
- Similar input and output energy flows



Technical Backup Slide: Argonne engine experiments

NGK
Conventional Spark

Current Focus

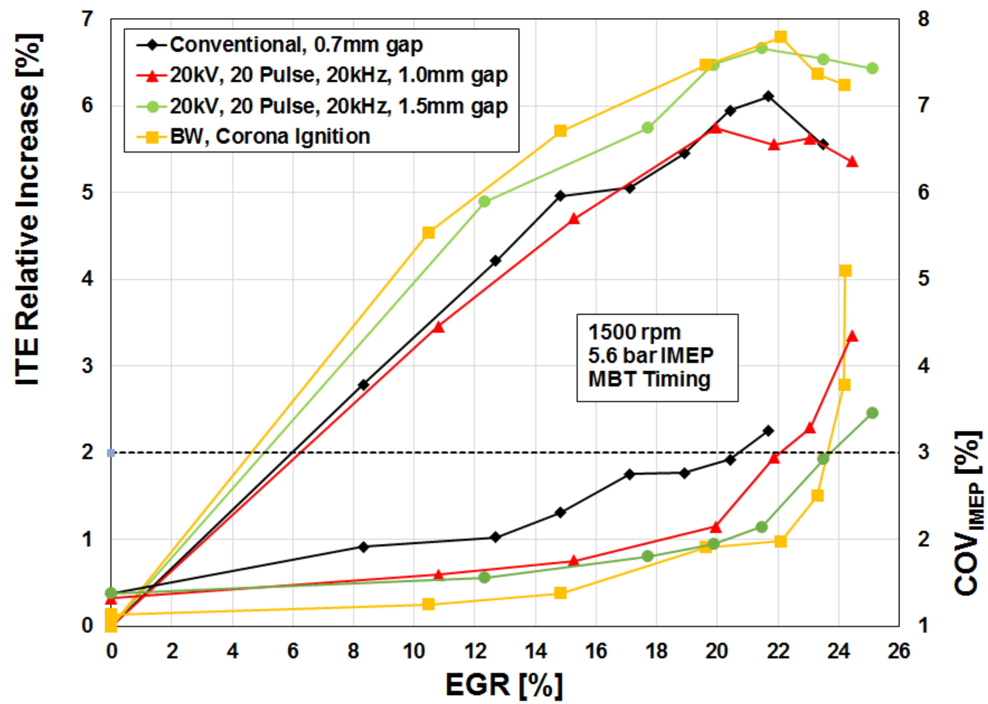
TPS Inc.
Close-Coupled PND

BorgWarner
EcoFlash RF Corona

Data and images courtesy of Riccardo Scarcelli - Argonne

Displacement	0.6 L
Bore x Stroke [mm]	89.04 x 100.6
Compression Ratio	12.1:1

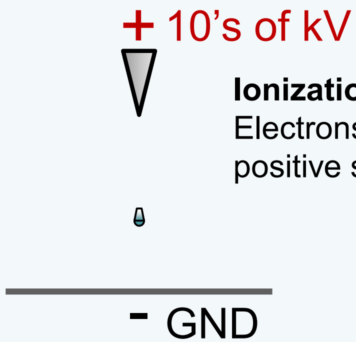
Similar results found for lean operation



- What is the ignition mechanism?
- How does EGR influence discharge phenomena?
- What prevents further dilution limit extension?

Technical Backup Slide: LTP discharge phases

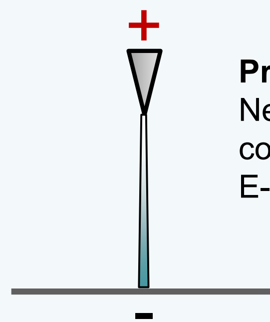
1. Primary streamer phase



Ionization by primary streamer head.
Electrons move towards anode leaving positive space charge in streamer path.

Δt ~ $\mathcal{O}$(1 ns)

2. Compensation phase



Primary streamer connects to cathode.
Negative charge flows from cathode to compensate positive space charge.
E-field increases near anode.

3. Secondary streamer phase

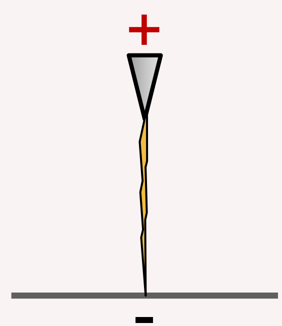
LTP

Secondary streamer advances.
Strong E-field near anode leads to rapid advance.

Δt ~ $\mathcal{O}$(10 ns)

SSB

4. Transient arc phase

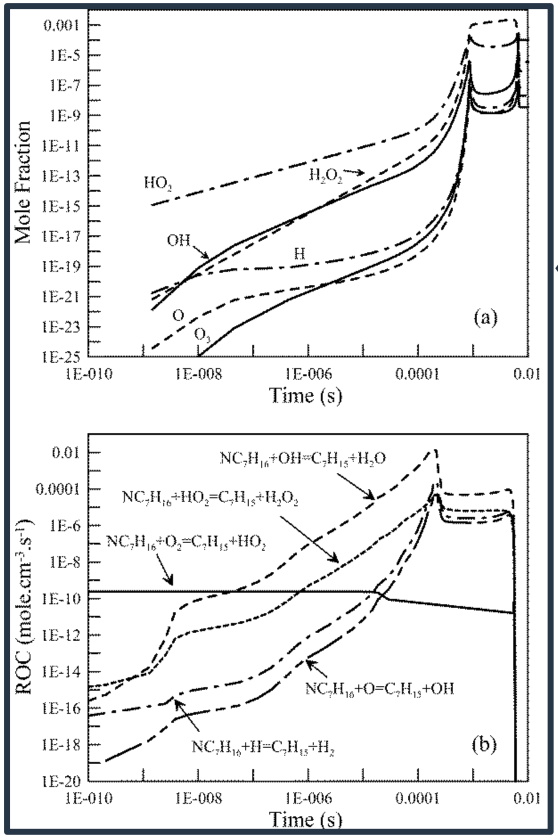


Arc occurs if secondary streamer reaches cathode (*E*/*N* high along the entire discharge filament).
Secondary streamer propagation promoted by local heating from V-T relaxation (reduction in *N*).

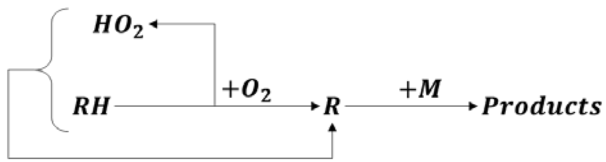
Marode, J. Appl. Phys., 1974;46(5).
Bastien & Marode, J. Phys. D: Appl. Phys., 1985; 18(377).

Close-coupled PND (100 μs dwell) aim to increase **radical formation** while ideally **avoiding secondary streamer breakdown** (SSB)

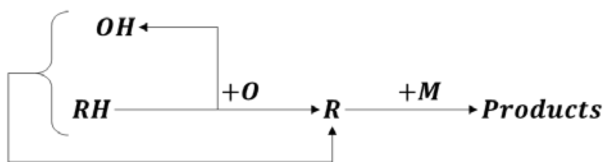
Technical Backup Slide: Impact of O-atom on LTHR

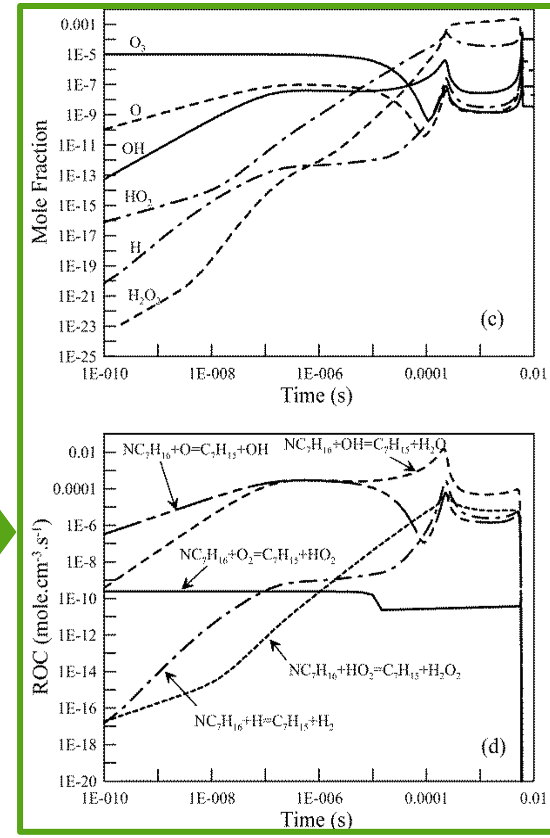


Without ozone



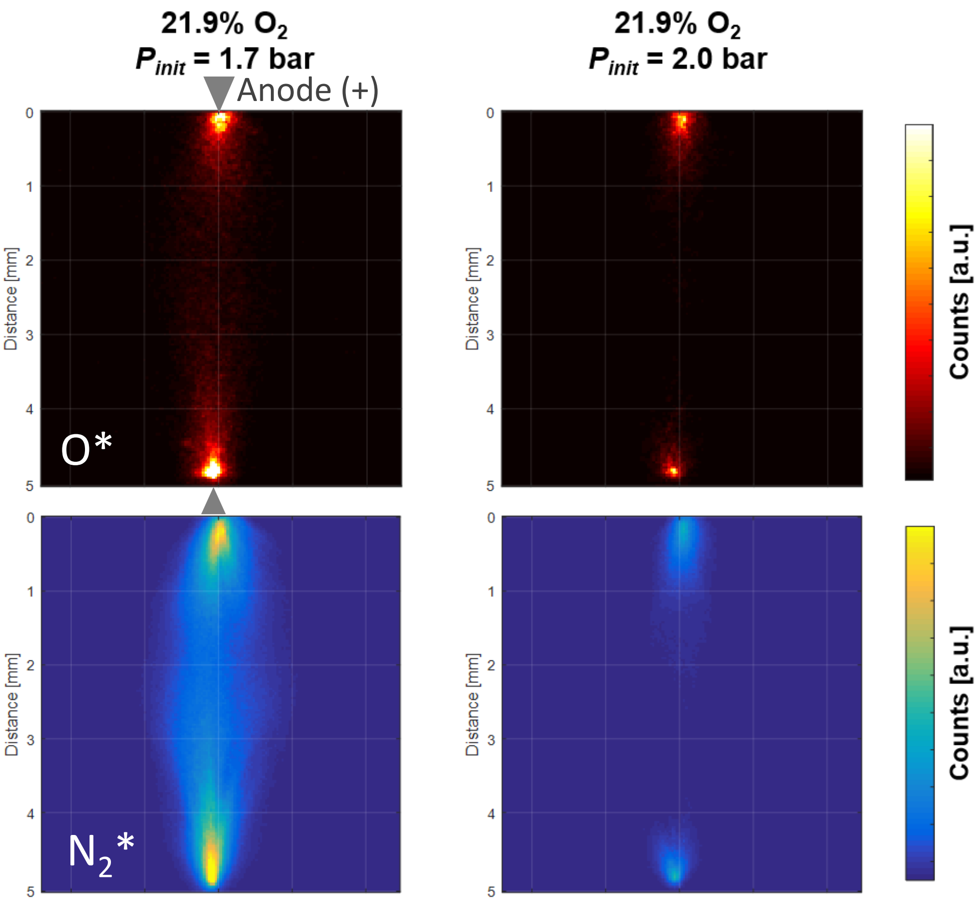
With ozone





Uncertain kinetic modeling at engine relevant conditions

Technical Backup Slide: Influence of pressure on emission



Increasing pressure at constant composition

Single pulse
Top = O*: 500 ns gate
Bottom = N_2*: 500 ns gate

O*: O($3p^3P \rightarrow 3s^3S$) at 844.9 nm

- Image intensity changed -61% for $\uparrow P_{init}$
  - Estimated change in fluorescence quantum yield (FQY) = -15%

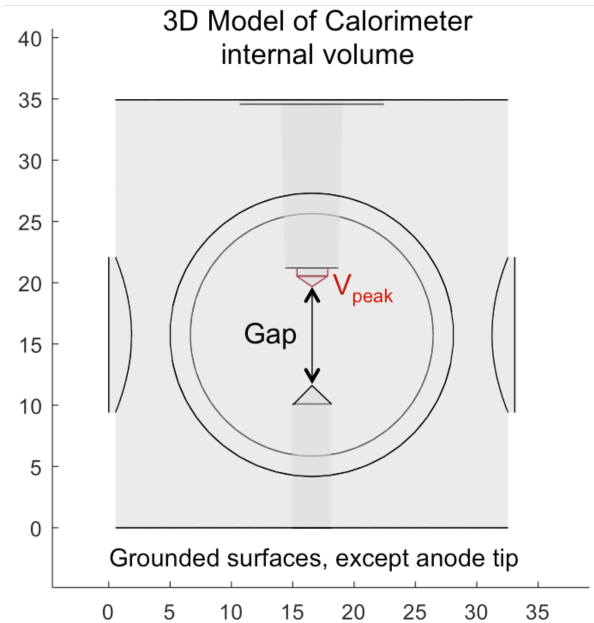
N_2*: $N_2(C^3\Pi_u \rightarrow B^3\Pi_g)$ at 337.1 nm

- Image intensity changed -75% for $\uparrow P_{init}$
  - Est. change in FQY = -15%

Suggests other factor important, e.g. E/N

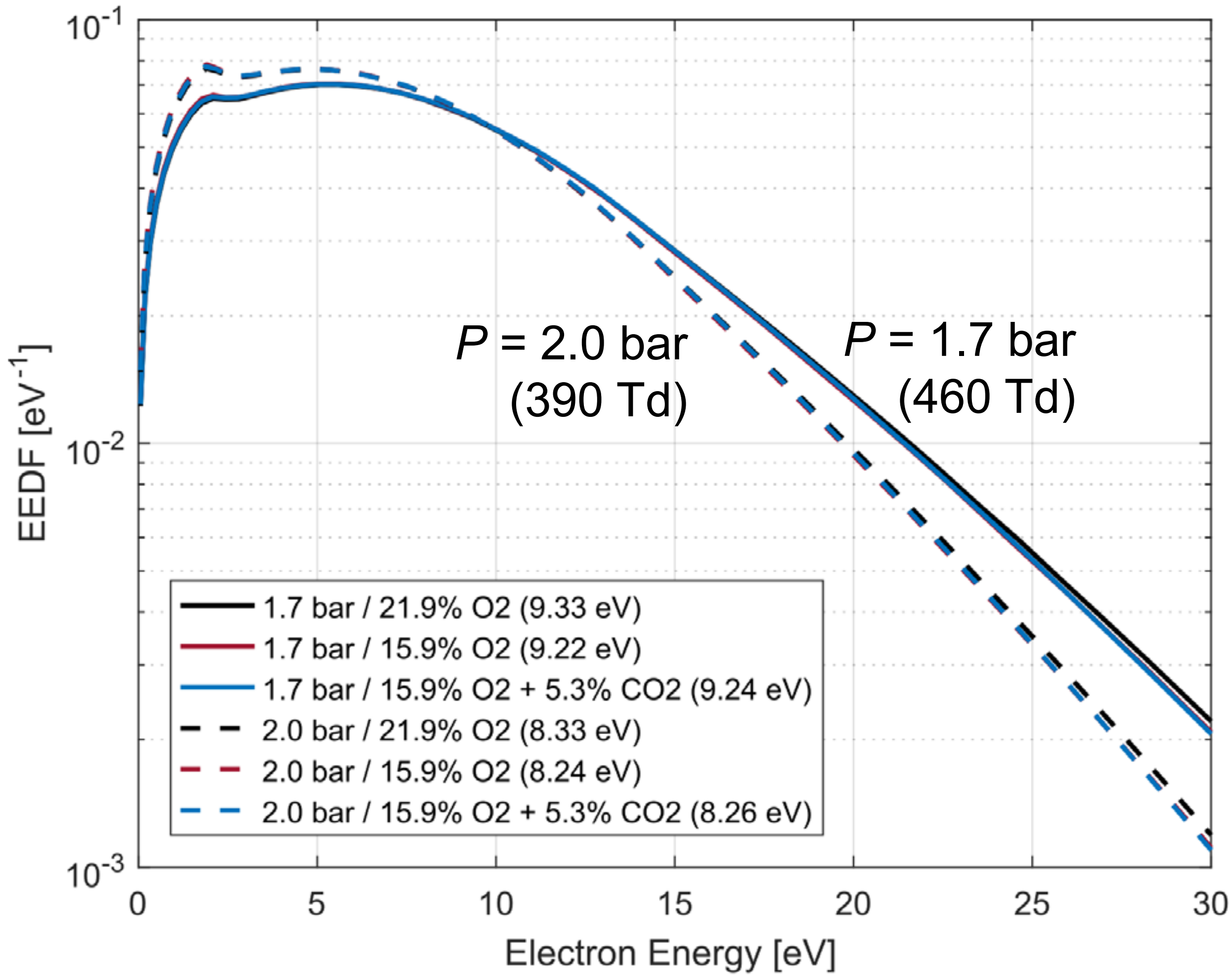
Technical Backup Slide: Estimated LTP EEDF

MATLAB model to estimate E/N



BOLSIG+ to estimate EEDF

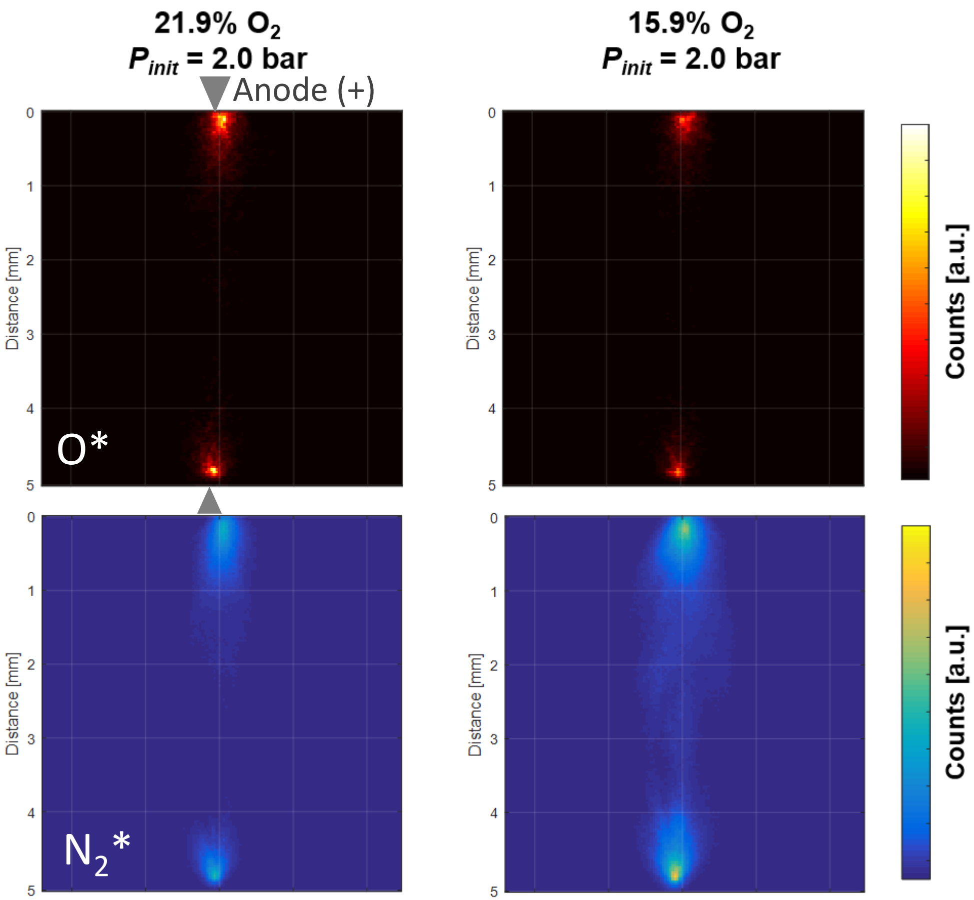
E/N, composition, temperature, and collision cross-sections of O_2, N_2, CO_2 (attachment, elastic, rot./vib. excitation, ionization)



Impact of increased pressure may be explained by EEDF

Note: impact of pressure > impact of gas composition

Technical Backup Slide: Influence of O_2 on emission



Decreasing X_{O2} at constant pressure

Single pulse
Top = O*: 500 ns gate
Bottom = N_2*: 500 ns gate

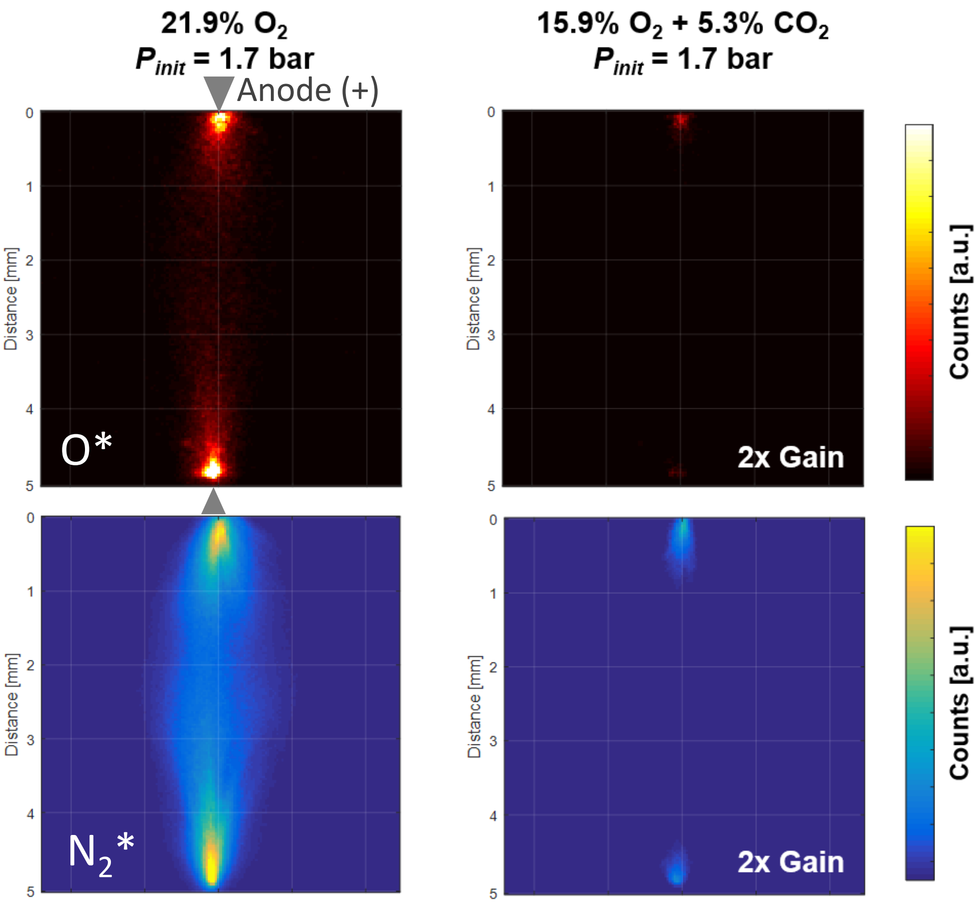
O*: O($3p^3P \rightarrow 3s^3S$) at 844.9 nm

- Image intensity changed $\boxed{-27\%}$ for $\downarrow X_{O2}$
  - Estimated change in FQY = +4%
  - Change in X_{O2} = -28%
  - Total est. change = $\boxed{-24\%,}$ **agrees well**

N_2*: $N_2(C^3\Pi_u \rightarrow B^3\Pi_g)$ at 337.1 nm

- Image intensity changed $\boxed{+85\%}$ for $\downarrow X_{O2}$
  - Estimated change in FQY = +30%
  - Change in X_{N2} = +8%
  - Total est. change = $\boxed{+38\%,}$ **right trend**
  - *Note*: single transition not isolated

Technical Backup Slide: Influence of CO_2 on emission



Increasing X_{CO2} at constant pressure

Single pulse
Top = O*: 500 ns gate
Bottom = N_2*: 500 ns gate

O*: O($3p^3P \rightarrow 3s^3S$) at 844.9 nm

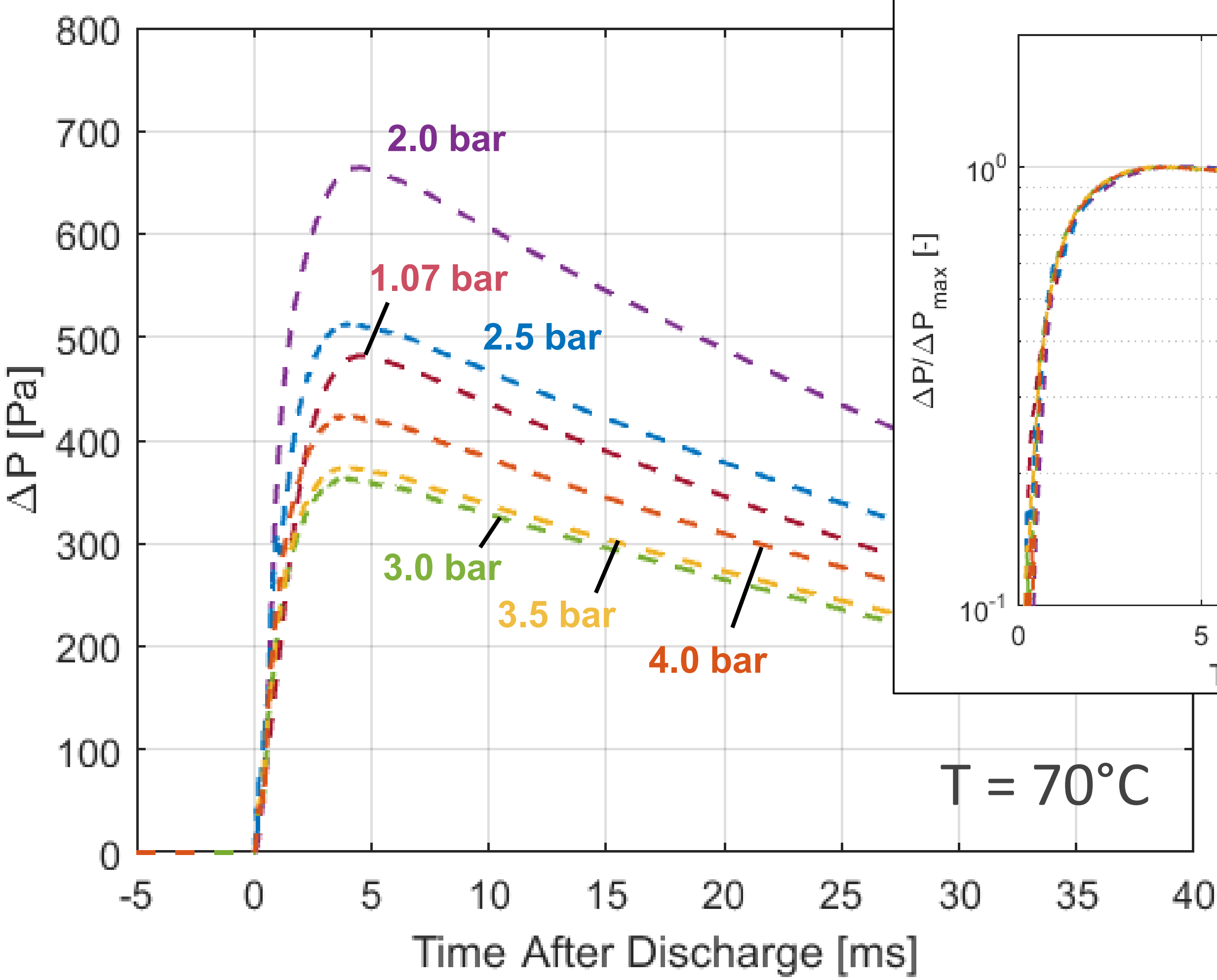
- Image intensity changed $\boxed{-92\%}$ for $\uparrow X_{CO2}$ & $\downarrow X_{O2}$
  - Estimated change in FQY = +3%
  - Change in O_2 conc. = -28%
  - Total est. change = $\boxed{-25\%,}$ **does not agree**

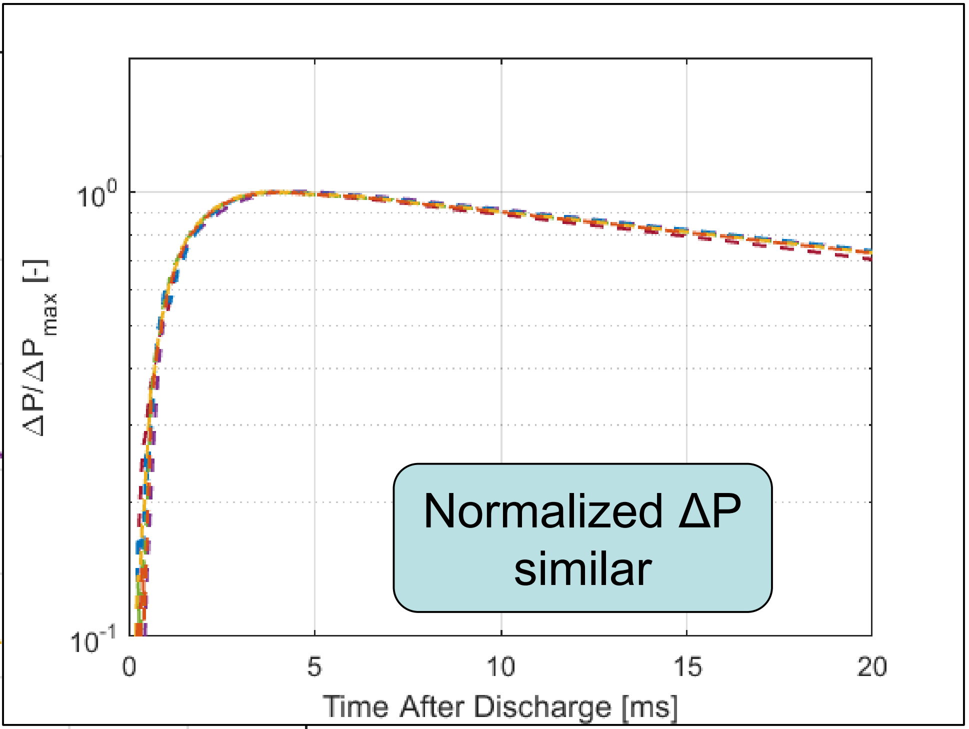
N_2*: $N_2(C^3\Pi_u \rightarrow B^3\Pi_g)$ at 337.1 nm

- Image intensity changed $\boxed{-91\%}$ for $\downarrow P_{init}$
  - Estimated change in FQY = -4%
  - No change in N_2 conc.
  - Total est. change = $\boxed{-4\%,}$ **does not agree**
  - *Note*: single transition not isolated

- Impact of CO_2 not explained by EEDF, quenching (or fluorescence trapping)
- Kinetics? ANL modeling effort.

Technical Backup Slide: Pressure calorimeter – arc

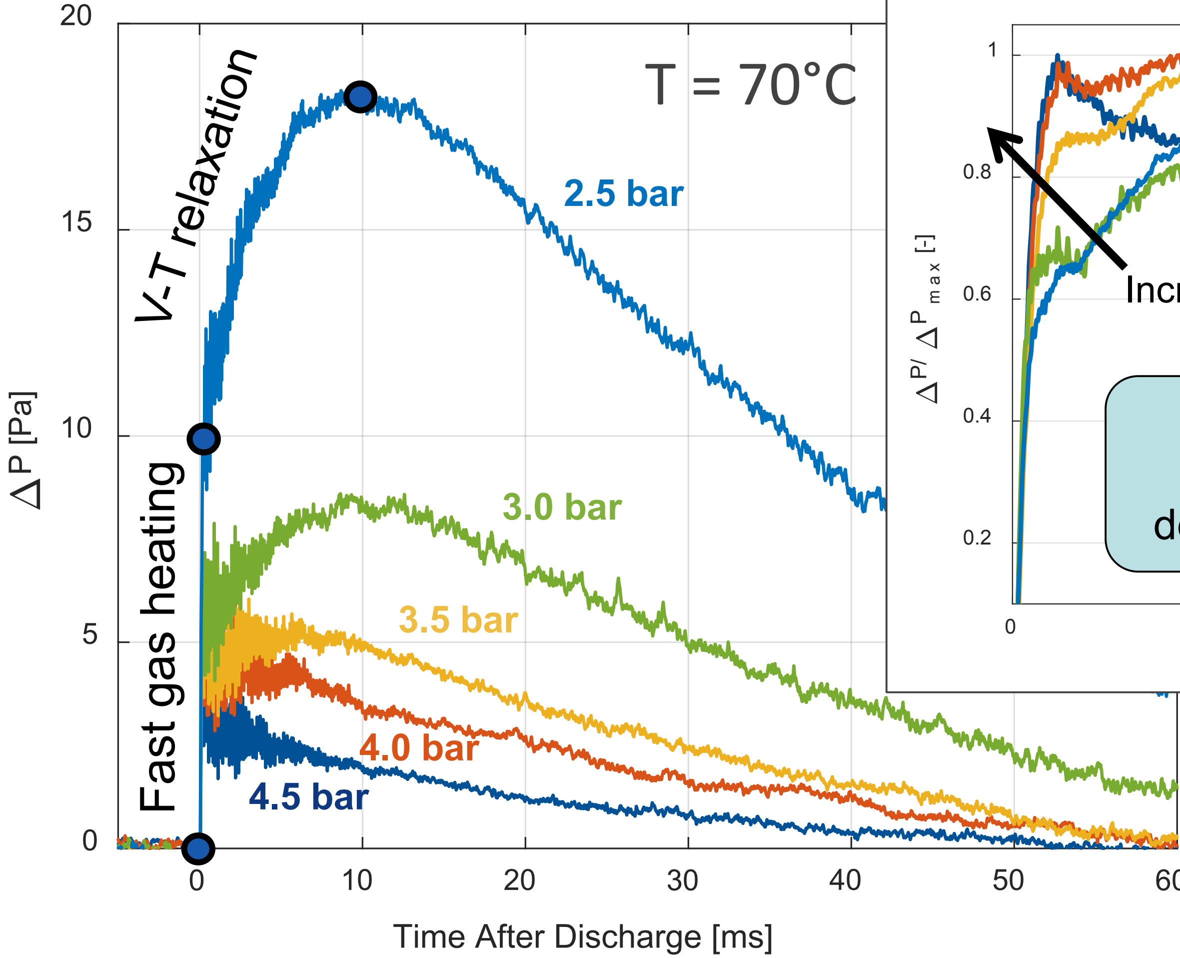


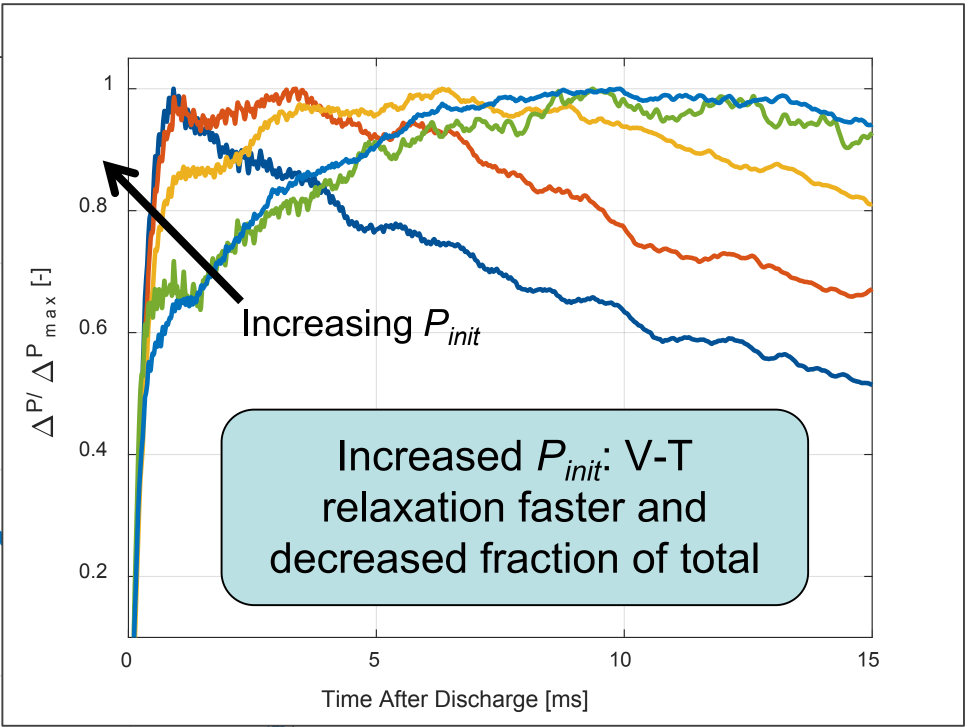


Normalized ΔP similar

Varied order with P_{init} suggests discharge behavior may be changing

Technical Backup Slide: Pressure calorimeter – LTP



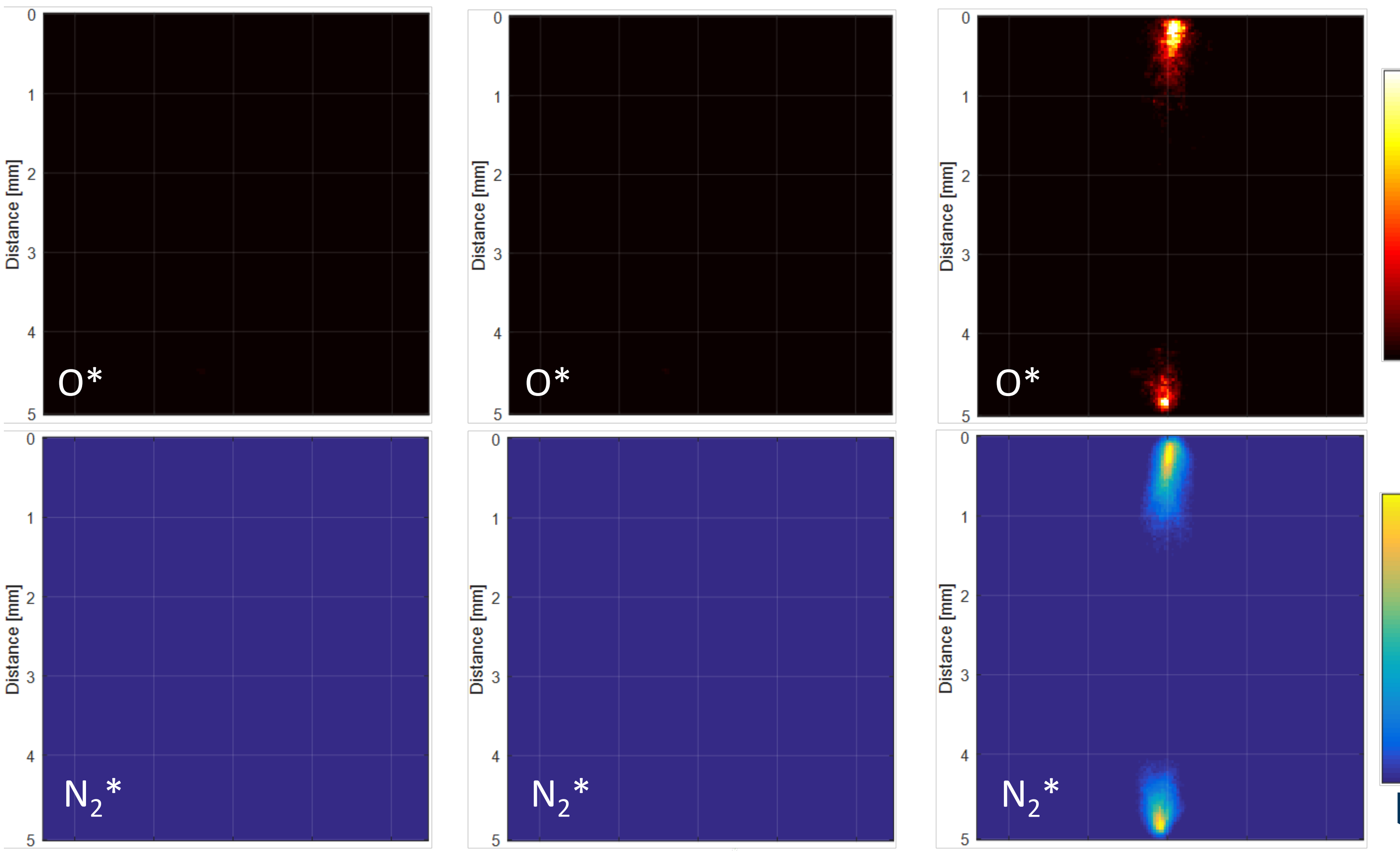


Increased P_{init}: V-T relaxation faster and decreased fraction of total

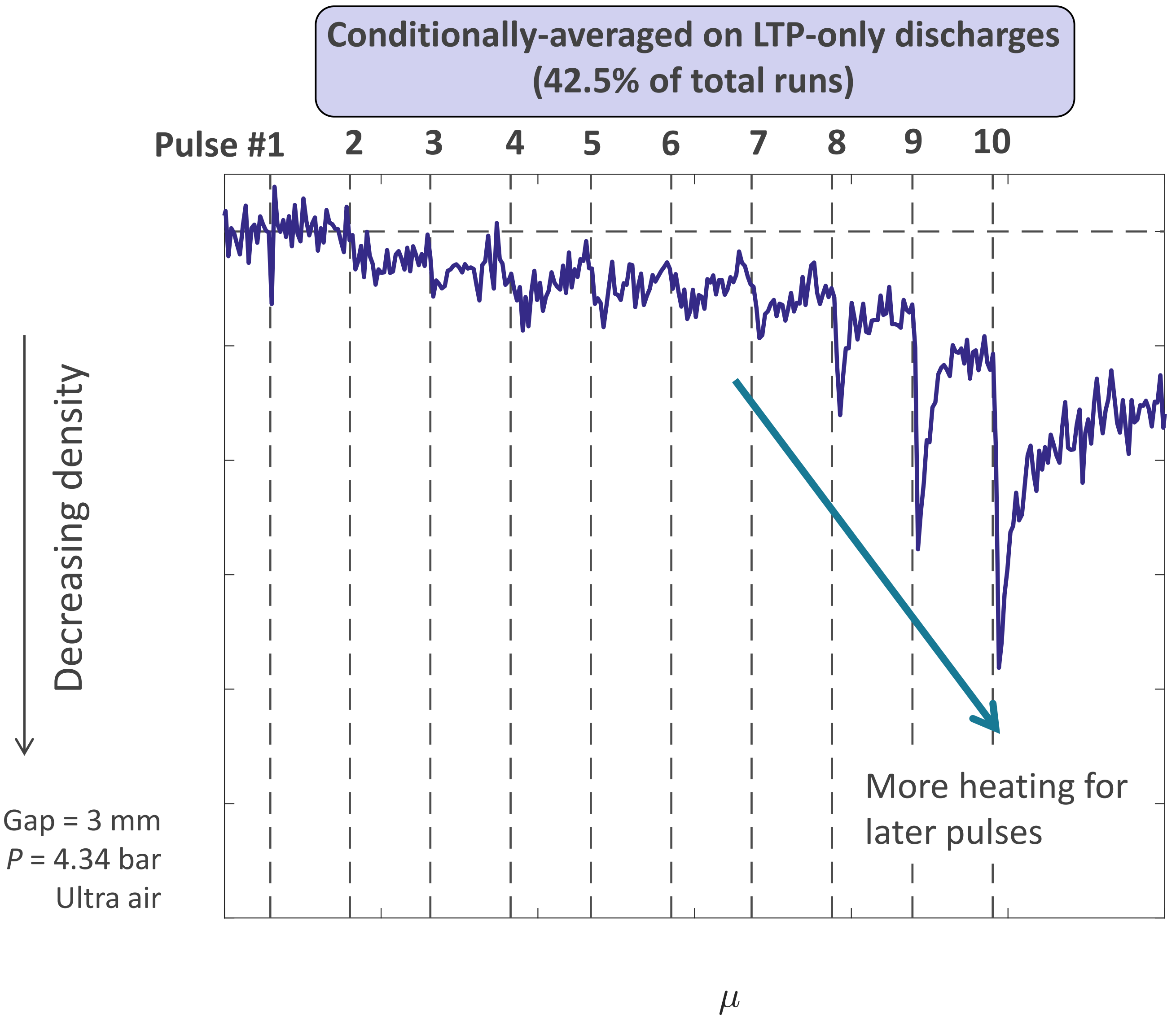
E/N falling with increased P_{init}: decreasing average electron energy, less excitation of higher energy transitions

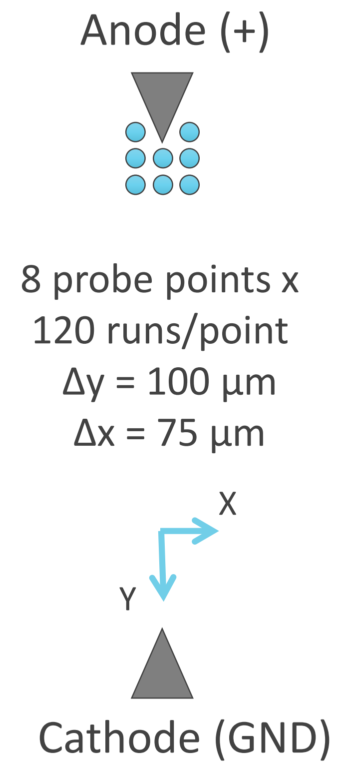
Technical Backup Slide: Emission with multi-pulse

21.9% O_2, P_{init} = 2.5 bar		21.9% O_2, P_{init} = 2.5 bar		21.9% O_2, P_{init} = 2.5 bar
1st Pulse	→	3rd Pulse	→	5th Pulse



Technical Backup Slide: Argonne APS x-ray radiography

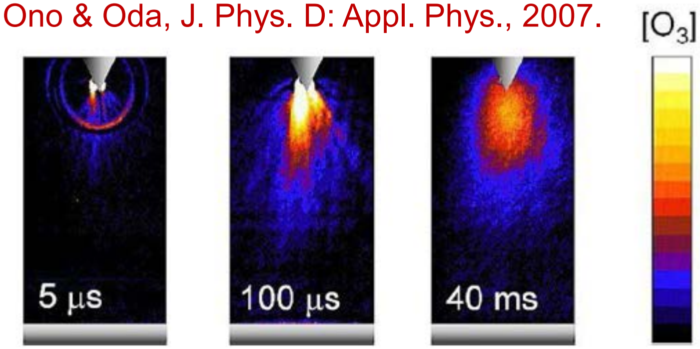


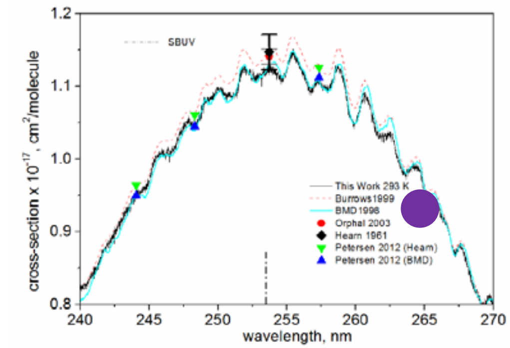


Measurements by:
A. Kastengren
D. Duke
K. Matusik

Technical Backup Slide: Ozone laser absorption

Ono & Oda, J. Phys. D: Appl. Phys., 2007.





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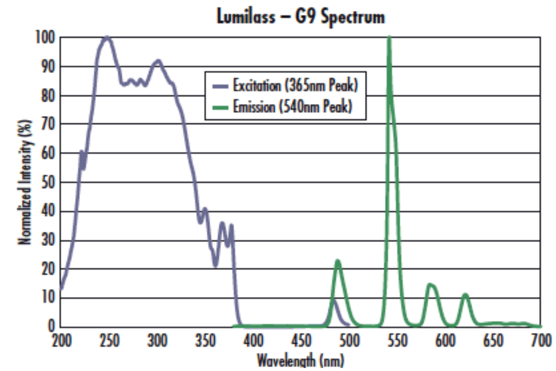

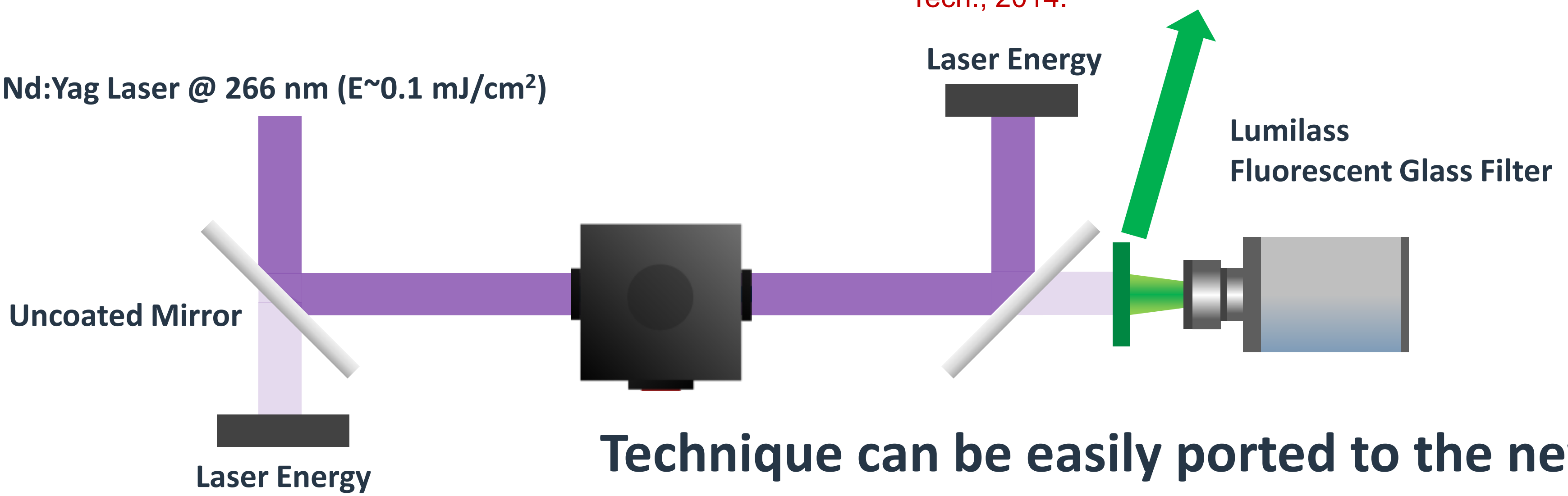

Technique can be easily ported to the new optically-accessible gasoline research engine